

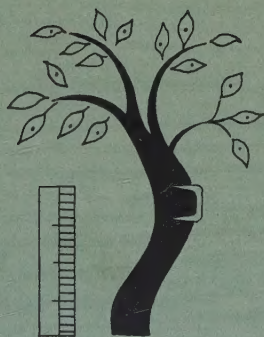
From the Department of Orthopedic Surgery,
University Hospital in Lund
Lund, Sweden

GROWTH PATTERNS AFTER PHYSEAL INJURY AND PHYSEODESIS OF THE KNEE

A Roentgen Stereophotogrammetric and
Scintimetric Analysis in Children

BIRGER BYLANDER

LUND 1982



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A Roentgen Stereophotogrammetric and Scintimetric Analysis in Children

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AKADEMISK AVHANDLING

som med vederbörligt tillstånd av Medicinska Fakulteten i Lund för avläggande av medicine doktorsexamen kommer att offentligen försvaras i Kvinnoklinikens Föreläsningssal, Lasarettet, Lund fredagen den 19 november 1982 kl 14.00.

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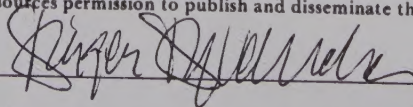
Organization LUND UNIVERSITY Department of Orthopedic Surgery University Hospital, S-221 85 Lund, Sweden		Document name DOCTORAL DISSERTATION	
		Date of issue November 19, 1982	
		CODEN: LUMEDW/MEOC 1012/01-53 (1982)	
Author(s) Birger Bylander		Sponsoring organization	
Title and subtitle GROWTH PATTERNS AFTER PHYSEAL INJURY AND PHYSEODESIS OF THE KNEE. A Roentgen Stereophotogrammetric and Scintimetric Analysis in Children			
Abstract Roentgen stereophotogrammetry and $^{99}\text{Tc}^m$ MDP scintimetry were used to analyse the growth dynamics in distal femur and proximal tibia in children after physeal injury and after physeodesis. Both methods were found of importance for the evaluation of growth disturbance. Temporary or permanent growth disturbance was found after physeal injuries. The predictive value of the Salter - Harris classification for growth disturbances after physeal injuries in the knee is limited. The pattern of growth retardation after Blount stapling is determined by skeletal maturity. The more advanced the skeletal age, the more pronounced and rapid the initial growth deceleration and the lower basal growth rate are obtained. Increasing growth rate from basal level and/or asymmetric growth are early signs of loosening of staples. Movements of the staples were registered. Widening of the staples and staple tip movements were found in all cases. Only in cases which later exhibited loosening of staples were staple tip movements pronounced. Provided basal growth is present, growth resumes after extraction of staples. An angular deformity following a physeal injury was corrected by medial stapling. A bony bridge seen on radiography probably corresponded to an osseo-fibrous bridge, since evidence of growth was registered. Pemister physeodesis, compared to Blount stapling, results in a more rapid growth retardation and growth arrest. Growth retardation after physeal injury or physeodesis results in low tracer activity. Increasing growth rate results in high activity.			
Key words Anisomelia - Fracture - Knee - Physeodesis - Physis - Roentgen stereophotogrammetry - Scintimetry			
Classification system and/or index terms (if any)			
Supplementary bibliographical information			Language English
ISSN and key title			ISBN
Recipient's notes		Number of pages	Price
		Security classification	

Distribution by (name and address)

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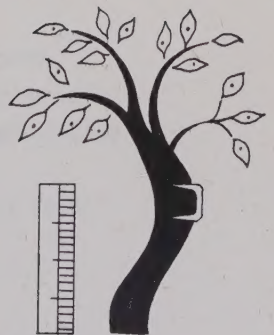
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Cover drawing: Rie Hägerdal.

we grow
we grow up
we grow older

(Goff 1960)

The present summary is based on the following publications.
They will be referred to by their Roman numerals (I - VII):

- I Bylander, B., Aronson, B., Egund, N., Hansson, L.I. & Selvik, G. (1981) Growth Disturbance After Physial Injury of Distal Femur and Proximal Tibia Studied by Roentgen Stereophotogrammetry. Arch Orthop Traumat Surg 98, 225-235.
- II Bylander, B., Hansson, L.I. & Selvik, G. (1982) Pattern of Growth Retardation After Blount Stapling. A Roentgen Stereophotogrammetric Analysis. J Pediatr Orthop (In press).
- III Bylander, B., Selvik, G., Hansson, L.I. & Aronson, S. (1981) A Roentgen Stereophotogrammetric Analysis of Growth Arrest by Stapling. J Pediatr Orthop 1, 81-90.
- IV Bylander, B., Hansson, L.I. & Selvik, G. (1982) A Roentgen Stereophotogrammetric Analysis of Growth Pattern After Extrac-tion of Staples. Acta Orthop Scand (Submitted for publication).
- V Bylander, B., Hansson, L.I. & Selvik, G. (1982) Dynamics of Growth Retardation After Phemister Physeodesis. A Roentgen Stereophotogrammetric Analysis. Acta Orthop Scand (Submitted for publication).
- VI Bylander, B., Hansson, L.I. & Selvik, G. (1982) Correction by Stapling of Progressive Angular Deformity After Physeal Injury of Proximal Tibia. A Roentgen Stereophotogrammetric Analysis. J Pediatr Orthop (Submitted for publication).
- VII Bylander, B., Hansson, L.I., Kärrholm, J. & Naversten, Y. (1982) Scintimetric Evaluation of Posttraumatic and Postoperative Growth Disturbance using $^{99}\text{Tc}^{\text{m}}$ MDP. Acta Radiol Scand, Diag-nosis. (In press).

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INTRODUCTION

Several factors influence longitudinal bone growth and cause anisomelia and/or angular deformity either by increased or decreased growth rate. Congenital anomalies and infections; inflammatory, vascular and neuromuscular disorders; tumours, trauma and physical and mechanical factors affecting the growth region often cause growth disturbance (Goff 1960, Morscher & Taillard 1965, Rang 1969, Tachdjian 1972).

In children, fractures involving the growth plates - physeal injuries - may cause growth disturbances. Permanent growth disturbance with progressive leg length discrepancy or asymmetric growth retardation resulting in a progressive angular deformity, are serious deformities after trauma to the growth region.

To correct progressive leg length discrepancy or progressive angular deformity in the child, surgical procedures (physeodesis) are available to retard or to arrest the longitudinal bone growth in the longer leg (Phemister 1933, Blount & Clarke 1949). These procedures have been advocated for correction or reduction by growth in leg length discrepancy of moderate degree. However, complications have been reported and information on the dynamics of growth retardation and the development of complications have been lacking, mainly due to insensitive techniques for longitudinal growth determination.

During the last decades the roentgen stereophotogrammetric (RSA) and scintimetric techniques have been improved. These techniques seem promising for determination of longitudinal growth dynamics and for early detection of growth disturbance.

REVIEW OF LITERATURE

Nomenclature

The nomenclature used in the literature for different parts of the growing long bone varies. The term *physis* or growth plate (Rubin 1964, Hansson 1967) is preferred to the terms epiphyseal growth plate, epiphyseal cartilage or epiphysis. The bony *epiphysis* and *metaphysis* are located on either side of the physis.

Physeal injury, i.e. fracture or separation through the growth plates is used in the present investigation since epiphyseal injury is not correct.

Physeolysis is used for the condition where the epiphysis is separated from the metaphysis through the physis.

Physeodesis is used for the growth retarding procedures designed by Phemister and Blount, respectively, since this term implies joining together of the bony epiphysis and the metaphysis. The term epiphyseodesis has previously been used but is not correct.

Longitudinal bone growth

Since Hales (1731), Belchier (1736) and Duhamel (1743) demonstrated the enchondral growth from the ends of the long bones, several investigations have dealt with the morphology and dynamics of bone growth (Hunter 1835, Ollier 1867, Harris 1931, Hansson 1967, Brighton 1980). The cellular arrangement of the different parts of the growth region has been thoroughly mapped (Harris 1931, Trueta & Morgan 1960, Hansson 1967). Vascular systems for the nutrition of the growth plate have been demonstrated and their significance for the enchondral growth pointed out (Trueta & Morgan 1960). The complex relationship between normal perichondral and enchondral growth processes have been demonstrated (Kember 1960, Siffert 1966, Langenskiöld et al. 1967, Hansson et al. 1972). Because of the consequences of leg length discrepancy and angular deformities, interest

has been focused on the longitudinal bone growth of the lower limbs (Haas 1926, Harris 1931, Green & Anderson 1947, Goff 1960, Tupman 1962, Anderson et al. 1963, Kember & Sissons 1976).

Growth determination

In order to register growth in long bones, various methods are available. Experimentally macro- and microscopical methods have been used to determine growth in a specific growth region. Originally, drillholes, metal markers (Hales 1731, Duhamel 1743) and staining by madder root (Belchier 1736, Duhamel 1743) were used in order to register longitudinal growth. Later, microscopical techniques in conjunction with intravital markers were applied (Aries 1941, Amako & Honda 1957). Hansson (1967) used tetracycline, visualized by fluorescence microscopy, to determine daily growth in length with high precision under experimental conditions. Autoradiographic techniques have been used experimentally (Leblond et al. 1950, Kember 1960). The increased tracer activity in the growth regions by various bone-seeking agents has also been demonstrated (Bauer 1968, Harcke 1978, Murray 1980, Walther et al. 1980).

Leg length can be assessed by standard radiographic techniques including slit scanography (Millwee 1937) and orthoradiography (Green et al. 1946, Bell & Thompson 1950, Taillard 1956, Goff 1960). Various types of markers have been used (Harris 1931, Brodin 1955, Anderson et al. 1963, Björk 1968). The sensitivity and/or accuracy of these methods is not satisfactory for closer growth analysis. The error of these methods varies between 1 - 10 mm (Morscher and Taillard 1965).

In 1974, Selvik presented his improvement of a roentgen stereophotogrammetric technique using spherical markers of tantalum inserted into the bone. The method, intended for clinical use, has a technical error of approximately 6 μm and a biological error of 30 μm , corresponding to a methodological error of 1 - 2 $\mu\text{m}/\text{day}$ at monthly measurements (Selvik 1974, 1978, Aronson 1976).

Prediction of growth and skeletal maturity

The normal growth pattern and the growth potentials proximally and distally in the femur and tibia have been extensively investigated (Digby 1916, Bisgard & Bisgard 1935, Gill & Abbott 1942, Green & Anderson 1947, Goff 1960, Tupman 1962, Anderson et al. 1963, Kember & Sissons 1976). The mean growth percentage of each growth region in the lower extremities is reported as approximately 70 per cent in the distal part of the femur. In the tibia the corresponding figure is 55 per cent for the proximal growth region. However, the percentage of growth varies with skeletal maturity (Hansson 1967).

The mean increment of growth per year in the femur and tibia varies in different investigations. Green & Anderson (1947) reported the average yearly growth in femur of boys as 2.0 cm and Goff (1960) as 1.3 cm.

Kember & Sissons (1976) compared growth determinations from lines of growth arrest in serial radiographs with the microscopical appearance of the growth plate in the distal femur, without taking skeletal age into consideration. The use of skeletal age rather than chronological age should have eliminated the phenomenon of the growth spurt observed during the adolescent years. This is explained by a corresponding acceleration in maturity in children who showed a period of increased growth in the preadolescent or adolescent years (Goff 1960, Tupman 1962).

Prediction of the growth potential was first introduced by Todd (1938) and later elaborated on by Gill & Abbott (1942) and by Bayley & Pinneau (1952). The prerequisite for all methods of prediction is information on the relative maturity or on the skeletal age of the child. The importance of skeletal age and its relation to longitudinal growth rate was firmly established by the studies of Anderson et al. (1963). For practical purposes, the radiographic atlas of the hand and wrist by Greulich & Pyle (1950) is sufficient. Apart from other atlases of the hand and wrist (Schmidt & Møll 1960, Eklöf & Ringertz 1967, Tanner et al. 1975) there are those where the knee (Pyle & Hoerr 1955) or the hip (Acheson 1957) is used as well. In the atlas by Schmidt and Møll (1960) the different skeletal maturity in boys and girls has not been taken into consideration.

During the last years interest has been focused on a method developed by Moseley (1977) called "the straight line graph". The accuracy of this graph is comparable to that of the tables of Green and Anderson (Stephens

et al. 1978). Contrary to the Green and Anderson-tables the Moseley graph is also valid in cases with abnormal longitudinal growth, and is today probably the best method for clinical use (Blair et al. 1982).

Physeal injury

Of all fractures in children approximately 15 per cent involve physeal regions (Poland 1898, Bergenfeldt 1933, Aitken 1965, Peterson & Peterson 1972, Tachdjian 1972, Ogden 1978). Of all physeal injuries some 30 per cent result in growth disturbance and about 3 per cent interfere with future function (Ogden 1978). The site of injury will govern the significance of the anticipated growth disturbance. The distal physes are injured more often than the proximal (Ogden 1981).

In order to predict the degree of growth disturbance and the future prognosis several classifications have been proposed (Foucher 1863, Poland 1898, Bergenfeldt 1933, Aitken 1965, Salter & Harris 1963, Tachdjian 1972, Ogden 1981). In recent reports (Lombardo & Harvey 1977, Cassebaum & Pattersson 1965, Burkhart & Peterson 1979) the injuries have been classified according to Salter & Harris (1963). However, the predictive value of the Salter and Harris classification has been questioned (Lombardo & Harvey 1977, Salter 1979, Petersen & Burkhart 1981, Ogden 1981). Ogden (1981) and Czitrom et al. (1981) pointed out that the mechanism of injury was an important factor in the prediction of future growth disturbance in growth plates adjacent to the knee.

Different opinions have been given on the treatment of physeal injuries, open or closed reduction and the period for immobilisation and no weight-bearing (Tachdjian 1972, Rang 1974). It is generally agreed upon that meticulous care must be taken to achieve anatomic reduction of a displaced fracture or fragment in order to restore the anatomy of the growth plate. The role of the periosteum, and the peripheral region of the growth plate in physeal injuries has been discussed (Salter & Harris 1963, Hansson et al. 1972, Ogden 1981).

Physeodesis

There are several methods for surgical treatment of linear and angular deformity (Phemister 1933, Blount & Clarke 1949, Goff 1960, Morscher & Taillard 1965).

Osteotomy has been recommended in the growing child and/or at termination of growth (Wagner 1978); distraction physeolysis according to Ilizarov has been introduced for correction of angular deformity and anisomelia (Franke 1980, Monticelli & Spinelli 1981), and stimulation through metaphyseal trauma has been used both experimentally and clinically in leg length discrepancy (Ståhl 1957, Hansson 1967, Hedström 1969). Langenskiöld (1967) succeeded in the operative elimination of a physeal defect. This method was successfully used in an experimental study by Österman (1972).

The most used methods for correction by growth are physeodesis according to Phemister and stapling according to Blount resulting in reduction of the growth of the longer leg.

The Phemister technique, has been recommended for the treatment of linear as well as angular deformities (Österman 1972). The technique aims at achieving complete and permanent growth arrest. Since the procedure is irreversible the question of prediction and accurate timing of surgery is essential (Blair et al. 1982).

Blount (1949) introduced his method of temporary growth arrest. Staples are inserted over the growth plate, thus inhibiting growth by compression. The stapling procedure has been found suitable for correction of linear as well as angular deformities. Stapling has been warned against owing to risks for complications (Brockway et al. 1954, Goff 1960, Frantz 1971, Tachdjian 1972, Nordentoft 1964, Stephens et al. 1978). The causes of failure have been attributed to the staples and to improper surgical technique but the effect of the longitudinal and transverse growth processes on the staples has not been thoroughly investigated. Blount (1971) pointed out that stapling in the proximal tibia is technically more difficult because of the shape of the tibia. Experimental investigations have been performed to study the effect of stapling on the growth plate (Siffert 1956, Goff 1960, Hall-Craggs & Lawrence 1969, Christensen 1973) but studies of the effect on the human growth plate is scarce.

PURPOSE OF INVESTIGATION

The purpose of the investigation was:

1. to evaluate the applicability of roentgen stereophotogrammetry and $^{99}\text{Tc}^{\text{m}}$ MDP scintimetry for determining the growth patterns of the knee in children
2. to investigate growth patterns after physeal injury in the distal femur and proximal tibia
3. to determine the growth dynamics after Blount stapling for correction of leg length discrepancy with special reference to:
 - a) pattern of growth retardation
 - b) movements of staples in the bone and to search for specific growth patterns as early signs of staple insufficiency
 - c) growth pattern after removal of staples prior to skeletal maturity
 - d) unilateral physeal stapling for correction of angular deformity by growth
4. to determine the dynamics of growth retardation after Phemister physeodesis.

MATERIALS AND METHODS

Materials

A total of 27 children were investigated. Of these, 7 were described in more than one paper (Table I). The chronological age (CA) of 17 boys ranged from 7 years and 1 month to 15 years and 3 months. The CA of 11 girls ranged from 8 years and 8 months to 13 years and 7 months. All patients were treated at the department of Orthopedic Surgery, University Hospital of Lund.

Seven boys (I, VII) sustained physeal injuries (Table II).

Nine boys and 10 girls (II, III) were stapled according to Blount because of leg length discrepancy of various etiologies (II).

Two boys (IV) were studied following extraction of staples after over-correction of leg length discrepancy prior to skeletal maturity.

One boy (VI) was stapled medially to correct progressive angular deformation after physeal injury in proximal tibia.

Two boys (V) were subjected to Phemister physeodesis in distal femur and proximal tibia to reduce a progressive leg length discrepancy.

Three boys and one girl operated upon with physeodesis and 3 boys with physeal injuries were evaluated with $^{99}\text{Tc}^{\text{m}}$ MDP scintimetry (VII). The data obtained from 25 growth regions in these patients were compared to results of the simultaneously performed RSA.

Methods

Clinical examination. To assess the leg length and angular deformity, tape measurements and measurements with goniometer were performed regularly at clinical examinations. Gait pattern, the degree of pelvic tilting and the degree of compensatory scoliosis were registered. Furthermore, development of sex characteristics, weight and total length in standing and sitting position were registered.

Table I. Out of 27 patients, 7 were described in more than one paper. In the text they will be referred to by their original designation prefixed by the roman numeral of the pertinent article

Article	Case designation in respective articles					
I	1		4			
II	B6	B2		G5	B3	B4 B5
III		1				
IV						1
V	1					
VI			1			
VII	3	4		5	1	2

Table II: Cases, all males, with physal injuries

Case	CA at time of injury (years and months)	Type of injury (Salter & Harris)	Site of injury	Degree of displacement	Treatment	Implantation of markers (months after injury)	Growth dynamics (RSA) *
I:1	12-5	I	Dist fem	+++	closed reduction	2	↓
VII:8	11-8	I	Prox tib	(+)	no reduction	26	(↘)
I:2	14-8	I&II	Dist fem	++	open reduction staples & pin	2	↓
I:5	14-11	I&III	Prox tib	++	open reduction	1	↓
I:3	7-1	IV	Dist fem	+++	open reduction pins	2	↘
I:4	8-8	IV	Prox tib	+++	open reduction pins	1	↘
VII:7	11-6	IV	Dist fem	+	no reduction	9	(↘)

Symbols: (+) = un-displaced fracture, + = minor displacement, ++ = moderate displacement, +++ = severe displacement.

↘ = temporary growth retardation, ↘ = progressive growth retardation,
 ↓ = permanent growth arrest, (↘) = arrow within brackets indicate initial growth determinations not available.

* (Kärrholm, 1982).

Radiography. The fractures of the knee were classified according to Salter and Harris (1963). In the preoperative planning, orthodiagraphic radiographs were used in cases with leg length discrepancy (Norman 1968). Standard radiographs, AP and lateral view, were taken. In cases with angular deformity projections were taken to obtain a radiographical estimation of the deformity. In order to assess skeletal age (SA), radiographs of the non-dominant hand and wrist were taken and compared to the atlas of Greulich and Pyle (1950). The skeletal age was determined at the time of injury or preoperatively at the time of surgery and at time of orthodiagraphic determinations of the leg length.

To predict future growth and to determine the optimal time for corrective surgery, the tables of Green & Anderson (1947) were used, and since 1978, in combination with the straight line graph according to Moseley (1977).

Roentgen Stereophotogrammetry (I - VII). The technique according to Selvik (1974, 1978) was used to determine the three-dimensional dynamics of growth. In order to obtain radiopaque reference points for roentgen film measurements, tantalum balls were inserted into the bone. Spherical balls, 0.5 or 0.8 mm in diameter (Industrial Tectonics Inc., Ann Arbor, Michigan) were inserted on each side of the growth plate. In injured regions and in regions of surgery 3 to 6 balls were used, but in reference regions single balls in each segment were used. The implantation was performed with an instrument described by Aronson et al. (1974). The tantalum balls were implanted percutaneously or through the operative incision under local or general anesthesia. At the start of this investigation, only the region of surgery was provided with markers, but later on markers were implanted on the contralateral intact side and intact growth regions of the knee. The knee with tantalum balls was radiographed in a calibration cage provided with markers of known location. Two calibration systems, one with the two images on one film and the other using two perpendicular films (Selvik 1974, Model 1 A and 2, respectively) were used. The films were measured in a Wild Autograph A8, generally used for cartography. The spatial location of the markers in the bone were then computed in relation to the coordinate system in the cage. Longitudinal growth rate analysis was performed using the computer program GROWTH. In

regions provided with 3 or more balls on each side of the growth plate, a kinematic analysis was performed using the computer program KINEMA. The kinematic analysis determines the rotational segmental movements about the three cardinal axes, the transversal (X), the longitudinal (Y) and the sagittal (Z) axis.

Analysis of staple tip movements required examination in the cage model 1 A (Selvik 1974) and a modification of the KINEMA program.

Scintimetry (VII). A $^{99}\text{Tc}^{\text{m}}$ MDP scintimetric analysis and comparison with the RSA was performed in 7 children. Of all 28 growth regions evaluated, 25 were provided with markers, thus permitting a simultaneous comparison with the RSA.

The patients were given approximately 200 MBq $^{99}\text{Tc}^{\text{m}}$ methylene-diphosphate (MDP). In general, static images were obtained 4 to 6 hours after i.v. injection of the radiopharmaceutical agent. A conventional large field of view (LFOV) scintillation camera with a general purpose parallel hole collimator was used for imaging. Conventional scintigrams on polaroid films and transparent film were analysed. The count information was stored (matrix 64x64) with a dedicated computer (Gamma-11). Counts within regions of interest (ROI) of total or parts of the growth regions were selected and compared in the images. Soft tissue medially in the thighs and for bone activity in the diaphysis of the femur was determined. At 4 to 6 hours these activities corresponded to 2 - 10 per cent and 10 - 15 per cent, respectively, of the activity close to the growth plate.

Besides the information obtained with the computer, image filtering techniques (Metz 1969, Gustavsson & Pizer 1976) were used in an attempt to obtain improved images.

Histology (V). Biopsies from growth plates subjected to Phemister physeodesis were investigated in two boys. The specimens were taken medially from the distal femur in the first case and from the distal femur and proximal tibia in the second case, fixed in Bouin's solution and decalcified. Paraffin sections were prepared. The sections were stained in haematoxylin-eosin. The height of the growth plates were measured (Hansson 1967).

Operative procedures - Physeal injuries (I, VI, VII). Closed reduction and immobilisation in plaster was performed on one boy (I:1) with a severely displaced bony epiphysis of distal femur classified Salter & Harris Type I injury (Table II).

Open reduction and internal fixation with pins or staples were performed in 4 boys with Salter-Harris Type I + III and Type IV injuries in the distal femur and proximal tibia. No reduction or internal fixation was performed in 2 boys with Type I and Type IV injuries in the proximal tibia and distal femur.

In general all injuries were treated with a period in plaster and with no weight-bearing during the initial 2 to 3 weeks after the injury.

Implantation of tantalum balls was performed in local or general anesthesia at extraction of the fixation device but in 2 boys 1 to 2 years after injury when admitted because of angular deformity (VII:7, VII:8).

Operative procedures - Physeodesis (II - VII). Blount stapling was performed in 19 children and the Phemister operation was performed in 2 cases, to reduce leg length discrepancy by growth. The stapling procedure was performed to achieve temporary growth retardation and to obtain correction at maturity.

The operative technique described by Tachdjian (1972) was used for the Phemister and Blount procedures. In general, small straight staples of Vitallium^R were used. The proximal fibular growth plate was not stapled or explored. After the Blount procedure the patients were mobilized with weight-bearing and after the Phemister procedure with no weight-bearing during 3 weeks. Plaster fixation was not used.

RESULTS AND DISCUSSION

Methodological Aspects

This investigation includes cases analyzed on different aspects of localized growth disturbance in the knee region (Table I). The problems after traumatic physeal injury and after surgical intervention with growth (physeodesis), can be considered similar. In these aspects new techniques, the RSA and the $^{99}\text{Tc}^{\text{m}}$ MDP scintimetry, were used for growth determination.

Roentgen Stereophotogrammetry (I - VII)

The method has been used at the University Hospital of Lund since 1973 in investigations concerning growth disorders in children or related problems dealing with the kinematics of the skeletal system (Olsson et al. 1976, Aronson 1976, Rune 1980). The RSA has proved to be a sensitive and accurate method for studies of three-dimensional dynamics of growth. The biocompatibility of the tantalum balls have been investigated by Aronson (1976) and recently by Alberius (1982). Ethical considerations have been thoroughly discussed by Rune et al. (1980).

Marking. The markers consisted of spherical tantalum balls, 0.5 or 0.8 mm in diameter. Up to 6 balls were placed on each side of the growth plate. With more than one ball in a segment the stability of the markers was checked. The markers in the bony epiphysis always remained epiphyseal but the metaphyseal markers gradually became situated in the diaphysis with time. The superficial markers in the metaphysis were sometimes displaced to a subperiosteal position due to the remodeling process. These markers were not used when found unstable.

In growth regions subjected to injury or surgery, where it is of interest to detect asymmetric growth within the growth region, 3 or more markers are necessary. The markers in these regions should be placed medial-

ly and laterally in the bony epiphysis and metaphysis and spaced apart anteriorly and posteriorly and at different levels proximally and distally. Care has to be taken not to place the metaphyseal markers in the phery.

In growth regions subjected to Blount stapling, difficulties sometimes arise in the visualisation of the markers if the staple legs project over the markers in the bone.

Exposure performance. Two different calibration systems were used (Selvik 1974). During the initial part of the investigation cage Model 1 A was used, but was later only used occasionally or when interest was focused on the registration of staple tip movements within the bone.

The radiation dose was approximately 1/3 of a standard radiography of the knee (Gustafsson 1980). The gonads were always shielded by a lead cover.

Errors of the method. Two different sources of errors have been classified and elaborated on in a previous investigation (Aronson 1976).

1. Technical factors ascribed to the recording system.
2. Biological factors such as deformation/remodeling of bone and subsequent instability of markers.

It has been shown that errors of the first type are of minor significance in the type of investigations performed here, giving distance errors less than about 10 μm (Selvik 1974, Aronson 1976).

As regards errors of the second type the stability of the markers in each bone segment was checked continuously during the investigation. This was achieved by comparing the distance changes of the markers in each segment between the recordings. The markers were, except for a slight instability during the first month after implantation, in general without signs of instability.

The total error of the method has been estimated to approximately 30-50 μm for growth determination corresponding to an error of 1-2 $\mu\text{m/day}$ at monthly measurements.

The precision in determining rotation angles and translations between segments was calculated by re-evaluating films from the same day. The varus-valgus angulation could be determined with a precision of approxi-

mately 0.05° and the longitudinal growth with a precision of about $10\text{ }\mu\text{m}$ (III).

In measuring the staple tip movements within the bone, the identification of the staple tips could in some instances be difficult. The location of the tips of the staples was sometimes uncertain, since the legs of the staples could be partially projected over each other. However, by using the reference balls, failing tip coordinates could be supplemented from a second film.

The technical precision and accuracy in determining translation of the staple tips were better than 0.1 mm for the transverse (X) and longitudinal (Y) axes, and for the sagittal (Z) axis better than 0.4 mm (III). Thus, the distance between the two tips of a staple lying mainly in the Y-direction was determined with an accuracy of approximately 0.1 mm , compared with 0.01 mm for the distances between tantalum balls.

Scintimetry (VII)

Normal growth involves a considerable incorporation of calcium and phosphate for the mineralisation process in the growth region. It is possible to visualize this incorporation by autoradiography and scintimetry.

Lack of precise information on longitudinal growth in children with growth disturbances has previously made radionuclide bone imaging of these regions difficult to evaluate.

In the present investigation the initial vascular phase was in some cases recorded but did not add further information. Information was obtained in static images. Orthogonal projections of the posterior lateral and medial views were found to correlate satisfactorily with the images obtained of the anterior view. The converging pinhole collimator was used on some occasions, but significantly improved images were not obtained.

The RSA provides information about the longitudinal growth process in terms of the rates with which the long bones elongate. Contrary to this, the information from scintimetric investigations of the growth process using $^{99}\text{Tc}^{\text{m}}$ MDP, is complex. $^{99}\text{Tc}^{\text{m}}$ MDP is incorporated during the growth and remodeling of bone and is localized temporarily, during the resorption process, in the calcified cartilage and bone and more or less definitely in the mineralisation process of cartilage and bone (Christensen & Krogsgaard 1981). A corresponding localization has previously been demonstrated for radioactive phosphorus (Leblond et al. 1950) and for tetra-

'cycline (Hansson 1964, 1967).

The radiation dose is low with $^{99}\text{Tc}^{\text{m}}$ MDP in the recommended doses for children (Saenger & Kereiakes 1975).

In conclusion, the growth process was measured with the RSA and $^{99}\text{Tc}^{\text{m}}$ MDP. The RSA is an invasive technique in contrast to scintimetry. The latter requires only one examination while RSA requires a minimum of two. The major advantage of the RSA is that it yields data in absolute values.

Intact growth regions - Normal growth rate (I, VI, VII).

Children with leg length discrepancy, not due to physeal injury, cannot be presumed to have a normal growth rate in growth regions of either the short or the long leg. However, the growth pattern in intact growth regions in cases with physeal injuries can be considered normal some months after the trauma.

The growth rate in the intact distal femur and proximal tibia in 2 boys with physeal injuries at the age of 8 years (CA) was approximately 50 μm and 25 $\mu\text{m}/\text{day}$, respectively, (I:3 and I:4) corresponding to an increment of 2 cm per year in the distal femur and 1 cm i proximal tibia. Deceleration, from approximately 50 $\mu\text{m}/\text{day}$ in the distal femur was initiated in boys at SA approximately 14 years and at 13 years in the proximal tibia. Termination of growth at skeletal maturity in boys occurred approximately 4 to 6 months earlier in the proximal tibia than in the distal femur (SA 16 and 16½ years).

The growth pattern in the intact proximal tibia in case I:1 showed short initial period of reduced growth rate. This pattern was seen in several intact growth regions in cases operated on with Blount stapling (II). This is probably caused by the trauma at injury or at operation (Gelin 1956, Bergentz 1961, Hansson 1967), by the pharmacological substances administered during general anesthesia and/or by the temporary immobilisation.

A preadolescent growth spurt was seen in two boys with physeal injury (I:4 and VII:7) and is probably explained by a simultaneous acceleration in skeletal maturity (Goff 1960, Anderson et al. 1963).

The values for normal growth rate as calculated from Green & Anderson (1947) and Kember & Sissons (1976) and the comparison with the values from the patients in the present investigation showed good agreement for cases with physeal injuries while the values from cases with physeodesis showed variations, as expected.

The skeletal age is determined by different developmental stages of the bones and accompanied by different growth rates in separate growth regions. Even if it might be difficult to assess skeletal age by using growth rates in absolute values, the RSA might in the future provide a means to determine skeletal age by comparing growth rates in different regions preoperatively.

Physeal injury (I, V, VI, VII)

In the following, the results from the different cases are presented and discussed. The investigation showed temporary or permanent growth disturbance in all seven cases studied (Table II).

Salter-Harris Type I

Case I:1, VII:5. Longitudinal growth rate analysis showed complete and permanent growth arrest in the injured growth region. Standard radiographs one year after the accident showed fusion of the injured distal femoral physis.

A scintimetric analysis was performed 32 months after the injury and showed very low tracer activity in the injured growth region. The complete growth arrest was probably due to a comprehensive damage to the growth plate caused by avulsion forces or by compression (Ogden 1981, Peterson & Burkhart 1981). In cases with displacement, although classified as Type I, the periosteal attachment is more or less completely ruptured. A central avulsion fracture from the bony epiphysis (Ogden 1981) cannot be excluded. The prognosis of these injuries are poor contrary to previous reports in the literature. The complete growth arrest in this case resulted in a considerable leg length discrepancy indicating physeodesis.

Case VII:8. The RSA showed reduced growth, especially in the lateral part of the injured growth region, resulting in valgus deformity.

Scintimetry 3 years after the injury showed reduced activity laterally corresponding to the injured growth region.

The asymmetric growth required corrective surgery. This case provides further argument against the Type V injury as an independent type and the difficulties to recognize the Type I injury at time of injury (Peterson & Burkhart 1981).

Salter-Harris Type I + III

Case I:2. The growth diagram revealed, 2 to 3 months after the injury complete and permanent growth arrest in the injured growth plate. Standard radiographs one year after the accident showed fusion of the growth plate in injured distal femur.

Type III injuries are generally considered to have a fairly good prognosis when reduced to exact anatomical position (Salter & Harris 1963, Ogden 1981). However, the use of staples and a pin close to the growth plate was not optimal and the possibility of interference with growth must be considered.

In this case the injury was classified as a combined Type I + III injury, because of the small epiphyseal fragment and displacement of the bony epiphysis. Aitken (1965) has in his classification system taken this type of fracture in special consideration.

In spite of complete growth arrest in the injured growth region, no significant leg length discrepancy developed.

Case I:5. The RSA showed complete and permanent growth arrest in the injured proximal tibia. However, in spite of exact anatomical reduction and the generally considered good prognosis, permanent and complete growth arrest occurred but no leg length discrepancy of importance developed until skeletal maturity.

Salter-Harris Type IV

Case I:3. The RSA showed an initial and temporary asymmetric growth retardation in the injured growth region. In this case the growth disturbance was insignificant in spite of the displaced fracture and the use of pins through or near the physis.

Case I:4, VI:1. A progressive and asymmetric growth retardation was registered with the RSA and the kinematic analysis showed progressive valgus and antecurvature deformity as well as a slight outward torsion of the injured tibia.

Standard radiographs, one year after the accident, showed a condensed area laterally in the injured growth region, simulating a bony bridge. However, with a bony bridge connecting the metaphysis and the bony epiphysis, growth would have been arrested completely. The reduced but continuous growth in the lateral part of the injured growth region is probably an indication of the existence of an osseo-fibrous connection.

This case was later treated with medial stapling (VI).

Case VII:7. The RSA showed an increased growth rate laterally which persisted during the subsequent period of investigation. One month after the implantation of the tantalum balls (10 months after the injury) scintimetry showed increased activity in the lateral part of the injured distal femur. Thus spontaneous correction occurred in this case as has been reported previously (Chadwick 1982).

In conclusion, the prognostic value of the Salter & Harris classification was found limited after injury to the growth plates in the distal femur and proximal tibia as has been proposed by Lombardo & Harvey (1977) and by Peterson & Burkhart (1981). A similar finding has been demonstrated for ankle injuries (Kärrholm, 1982). The reason is probably that Salter & Harris (1963) showed the prognostic value for physeal injuries in an experimental investigation. Furthermore, factors as the skeletal maturity, the injured region and the nature of the trauma are of importance.

Injuries of the knee are probably more often due to high-energetic trauma and thus carry greater potential risks for damage to the growth plate. Furthermore, the complex system of axes of motion in the knee joint and the complex ligamentous apparatus provide a high susceptibility for extreme forces acting on the growth plate at the time of injury.

The possibility of interference with growth by the fixation device should be considered. Exact anatomical reposition is mandatory. The localization of the fixation device should be carefully chosen. Pins or wires through the physis should be inserted in the longitudinal direction of the bone. Screws, if used, should be placed transversely above or below the growth plate. The fixation device should be extracted after healing of the injury (Rang 1974, Tachdjian 1972).

Physeal injuries of the knee region should be clinically and radiographically controlled during at least 1 to 2 years after the injury. Optimally, these injuries could be provided with markers at time of injury and examined early at follow up with the RSA. Scintimetry provides valuable information on growth. Repeated examinations at follow up are valuable.

Physeodesis

Blount stapling-anisomelia (II, III, VII).

Sufficient staples. The pattern of growth retardation is determined by skeletal maturity thus elucidating some of the previous unsettled questions regarding remaining growth potential and efficiency of staples.

A consistent pattern of growth retardation was observed in 16 out of 19 cases during the initial 24 months postoperatively. Some irregularities were noted, especially after stapling at lower skeletal maturity, and in the proximal tibia. The more advanced the skeletal maturity at the time of stapling, the more pronounced the primary growth retardation and deceleration in absolute values and the lower the basal growth rate.

The kinematic analysis showed the degree of re- and antecurvation and varus- and valgus deformity. Angular deviation was more pronounced when stapling was performed at younger skeletal age. In cases stapled in the proximal tibia, the varus angulation dominated.

Theoretically, stapling at younger age would result in more rapid growth retardation, as the gap between the staple legs would be expanded in shorter time as a result of the higher growth rate. This process would theoretically be delayed when the growth rate is slower. However, this

does not agree with the findings. The explanation is probably that the staples continuously move peripherally in relation to the bone and that the gap between the staple tips is continuously widened.

The movements of the staples could be analyzed in terms of translations and rotations of the tips and in relation to the segmental markers in the bone. The longitudinal translations were in most cases small as were the transversal movements. Pronounced differences between epiphyseal and metaphyseal tips could not be identified. Furthermore, the widening of staples was small (max. 2.5 mm).

Three cases, two boys (II:B3 and II:B6) stapled in the proximal tibia and one girl (II:G5) in the distal femur, were investigated with $^{99}\text{Tc}^{\text{m}}$ MDP scintimetry. The boys were investigated 1 and 17 months respectively after the stapling procedure and the girl on two occasions 3 and 18 months after stapling. The analysis showed reduced activity in the stapled growth regions and the quantitative analysis showed accordingly reduced ratios. The qualitative and quantitative analysis in the girl stapled in the distal femur showed reduced activity in the stapled growth region 3 months after stapling which was further reduced at the second examination 17 months later. The scintimetric analysis was corroborated by the simultaneously obtained growth determinations with the RSA.

Insufficient staples. In three boys, one stapled in the distal femur (II:B2) and two stapled in the proximal tibia (II:B4, II:B1), asymmetric and increasing growth rates were observed indicating insufficiency of the staples. Replacement of staples were later performed in all three cases.

The boy (II:B2, III:1) stapled in the distal femur was thoroughly investigated. After an initial period of asymmetric growth but reduced laterally and medially, the subsequent two years showed slow, continuous growth (basal growth), slightly higher laterally than medially. An increasing asymmetric growth was then noted.

The epiphyseal tips of the staples moved more than the metaphyseal ones in the transverse direction, indicating tilting of the staples. Some of the staples moved in the preformed channels at the operation, but others moved outside these channels indicating that the staples cut through the bone or that there was bone resorption around the staple-leg. The widening of the staples could be determined and amounted in this case to at

most 6.2 mm in one of the lateral staples.

Scintimetry was performed on two occasions, 43 and 47 months after the operation. The tracer activity was reduced in the stapled growth region. However, at the first examination, although activity was reduced in the growth region, no differences could be recognized medially and laterally. Four months later when the growth rates were further increased and the asymmetric growth even more pronounced (8 m/day medially and 15 m/day laterally), scintimetry showed still reduced activity compared to the intact growth regions but increased activity especially laterally, compared to the previous investigation.

The kinematic analysis showed progressive varus deformity increasing markedly during the final months prior to reoperation. The standard radiographs confirmed the findings and showed that the extrusion and widening of staples was especially pronounced laterally. The staples were replaced 48 months after stapling. The operative findings confirmed loosening of the staples.

It can not be excluded in this case that the staples during the first two years were sufficient since a low basal growth was registered. The stapling in this patient was performed comparably early with an increased risk for staple insufficiency (Blount 1971).

The two boys (II:B1 and II:B4) stapled in the proximal tibia showed pronounced asymmetric growth and progressive angular deformity. They were 8 and 11 years old (SA) when stapled. One of these (II:B1), showed a primary growth retardation but during the subsequent two years an increasing growth rate, especially laterally until replacement of staples was performed 32 months after stapling.

The other boy (II:B4) showed a reduced growth rate initially on the medial aspect but less pronounced laterally. This asymmetric growth continued at about the same rate for two years when increasing growth rates were registered medially and laterally. Scintimetric analysis in this case revealed reduced tracer activity but only slight differences were registered medially and laterally 16 months after the stapling procedure. A progressive varus and recurvatum deformity developed, and replacement of the staples was performed 37 months after stapling.

The state of biological development is likely to influence the frequency of insufficient growth retardation after stapling. This agrees with Blount & Clarke (1949), Green & Anderson (1957) and Poirier (1968) who found remaining growth especially pronounced after stapling in the proxi-

mal tibia. Insufficient growth retardation has been attributed to difficulties in insertion of the staples, to the construction of the staple, or to the tubulation of the metaphysis (Blount & Clarke 1949, Trias et al. 1961). Growth at a low basal level is probably not a failure of the staples to control growth but is preventing growth arrest. Probably it is the result of movements of the staples in the bone. Increasing growth rates indicate early signs of insufficient staples as seen in all three cases with replacement of staples. Improperly positioned staples are known to cause loosening and often asymmetric growth (Tachdjian 1972). However, there must be other explanations. Scheller (1960) showed that the epiphyses of distal femur and proximal tibia grow considerably in peripheral directions but at decreasing rates with skeletal maturity and that the proximal tibial epiphysis grows more in width with higher age compared to the distal femoral epiphysis. This growth results in transverse movements of the staples and a risk of extrusion, especially in the proximal tibia and in cases of early stapling. Thus, the reason for loosening of the staples in the present investigation is most probably the transverse growth in width of the bony epiphysis and metaphysis and the movements of the staples and probably not improper surgical technique as the staples were inserted according to the principles given by Blount & Clarke (1949) and Tachdjian (1972).

Growth pattern after extraction of staples (IV). Two boys were investigated following extraction of staples in the proximal tibia (IV:1), and in the distal femur and proximal tibia (IV:2). At time of extraction, the standard radiographs showed partial closure of the stapled growth region in the proximal tibia in the first case and neither growth region showed signs of fusion in the second case. The skeletal ages at time of surgery were below or approximately 15 years of age.

No resumption of growth was registered in the boy stapled in the proximal tibia 38 months prior to extraction. The growth plate was partially closed as seen on standard radiographs at time of extraction (IV:1).

In the other boy (IV:2), the staples in the proximal tibia were extracted 44 months after initial stapling. The RSA during 9 months after extraction showed bilateral and symmetric deceleration until maturity.

The staples in the distal femur were extracted 27 months after stapling and growth analysis showed continuous bilateral and symmetric growth de-

celeration until maturity and termination of growth occurred simultaneously in the left and right distal femur (IV:2).

These findings are in agreement with earlier studies (Blount & Zeier 1952, Green & Anderson 1957, McGibbon et al. 1962, Nordentoft 1964) indicating that resumption of growth cannot be expected if the staples are extracted less than about one year prior to termination of growth in intact growth regions at the knee. There were no indications of growth stimulation after the removal of staples or premature closure of the previously stapled growth region as Blount & Zeier (1952) stated. The ability to resume growth after removal of staples is probably lost shortly before complete growth arrest after stapling.

Skeletal age has to be considered in the preoperative planning. If early stapling is performed, staples must be extracted after slight over-correction. To permit stapling at a time which will yield coinciding leg length at maturity the methods for predicting remaining growth must be improved as the existing techniques are inexact. These difficulties in growth prediction may possibly be reduced, using the RSA before physeodesis, as the growth rates of the actual growth regions are possible to determine, as also is skeletal maturity by comparing different growth regions in the same individual.

In conclusion, three-dimensional growth dynamics in children can be determined with the RSA. This method is suitable to check growth after the stapling procedure. The efficiency of the staples can be determined and signs of loosening can be detected early. The movements of the staples can be analyzed with the RSA, thus elucidating the mechanisms of the influence of growth on the staples within the bone.

For the preoperative planning single pairs of markers are implanted bilaterally in distal femur and proximal tibia. This provides information about the growth potential in the short and long leg. Additional markers are implanted medially and laterally in the region of surgery at time of stapling, to provide information on the growth dynamics postoperatively.

Scintimetry is of value to provide further information about the dynamics of growth. Scintimetry is non-invasive, easy to perform and gives information at a single examination. However, the scintimetric analysis represents the state of metabolic turnover in the growth region; while the RSA provides data on longitudinal growth.

Blount stapling - angular deformity (I, VI).

An injury in the lateral part of the proximal tibia resulted in progressive valgus deformity (I:4, VI:1). The growth rate decreased laterally after the injury but with no signs of complete growth arrest, indicating the formation of an osseo-fibrous connection between the bony epiphysis and metaphysis.

After the stapling procedure medially, the growth rate increased laterally and decreased medially. The valgus deformity was thus eliminated and at overcorrection the staples were removed. Extraction resulted in a temporary increase of the growth medially, probably as a result of the elimination of the compression forces medially from the staples. Almost normal and symmetrical growth was registered after the initial postoperative month following the extraction.

In this case the radiographs showed an area of condensed bone usually interpreted as a bony bridge (Johnson & Southwick 1960, Langenskiöld 1967, Österman 1972). After the stapling procedure medially, the area of condensed bone appeared to shift gradually in metaphyseal direction by growth from the physis.

The period of follow up after the extraction of staples is short in this case, but the results from the growth analysis in combination with the radiographical appearance of the growth region indicate that symmetrical and almost normal growth probably will continue even if there are irregularities in the growth plate corresponding to the area of injury.

In conclusion, the RSA gives information about growth disturbance after physeal injury. To correct the deformity by growth, the decision for surgical procedure is guided by the RSA. The bony bridge seen on standard radiographs in the growth plate is probably of osseo-fibrous origin in cases with evidence of growth. Unilateral stapling is an alternative to the Langenskiöld operation.

Phemister physeodesis (V, VII)

Following the Phemister operation in the left distal femur (V:2), the growth rate was immediately reduced to low level. Complete growth arrest occurred within 6 months.

The microscopic analysis showed the cellular arrangement of an active growth plate. The height of the columnar zone was about 500 μ m, corresponding to a growth rate of 50 μ m/day as registered by the RSA, and in agreement with the values presented by Kember & Sissons (1976). A condensation line or line of growth arrest was demonstrated in the left distal femur, representing the physeal injury on the contralateral side 15 months earlier. The distance between the condensation line and the growth plate was approximately 20 mm, corresponding to the accumulated growth of 17.8 mm measured with the RSA over a slightly shorter period.

A scintimetric analysis was performed 17 months after surgery and showed reduced activity in the growth region with Phemister physeodesis.

In the other boy (V:1), only growth rates after surgery are available, as markers were implanted at the Phemister physeodesis. The growth rates in the distal femur and proximal tibia were low immediately after physeodesis, and decelerated to growth arrest within months.

However, the growth potential at the time of surgery could be estimated with microscopic analysis of the growth plates cut out at surgery and from the condensation lines in the distal femur corresponding to the diaphyseal fracture of the right femur. The height of the columnar zones in the left distal femur and proximal tibia were approximately 400 μ m, corresponding to a growth rate of 30-40 μ m/day as calculated from the condensation line in the left distal femur. This is in good agreement with the estimated values on the basis of the postoperatively registered growth rates in the distal tibia and fibula on the same side, which on the other hand were considerably higher than on the fractured side. The origin of the markedly low growth rates on the fractured side is not known but the registration of the low growth rates explains the postoperative course.

The primary growth retardation resulting in growth arrest within months is explained by the formation of callus or osseo-fibrous areas in the growth plate after the Phemister operation. Later on, the growth is completely arrested since osseous connections develop in the osseo-fibrous areas resulting in fixation of the bony epiphysis to the metaphysis.

In conclusion, the growth rate following the Phemister physeodesis decreases more rapidly to complete growth arrest than after Blount stapling. Microscopical analysis of biopsies from growth regions provides information of the growth potential at the time of surgery. Scintimetry gives further information about growth after surgery and is valuable to check the efficiency of the Phemister procedure.

GENERAL SUMMARY

The complex dynamics involved in bone growth and remodeling have previously been investigated experimentally and clinically with various techniques under normal and pathological conditions. Methods for determining growth in separate growth regions in children have been insensitive. With the development of the roentgen stereophotogrammetric analysis (RSA) a technique for the determination of longitudinal growth and the segmental rotations and translations became available.

RSA was performed to evaluate the growth dynamics of the knee in children following physeal and physeodesis injury. The growth rate determinations obtained with the RSA made it possible to evaluate the information with a simultaneously performed $^{99}\text{Tc}^{\text{m}}$ MDP scintimetric analysis.

Physeal injury was studied in seven children. The anatomical classification of Salter & Harris was used. Complete growth arrest was registered in three cases with Type I injury in the distal femur or with Type I + III injury in the distal femur or proximal tibia. Progressive and asymmetric growth retardation was registered in two cases with Type IV and Type I injury in the proximal tibia. Temporary and asymmetric growth retardation was registered in two cases with Type IV injuries in the distal femur.

The Salter & Harris classification is useful for understanding the fracture anatomy but is of limited value for predicting future growth. The RSA rapidly reveals growth disturbances. The method facilitates the time for and choice of operative procedure. Scintimetry provides information on growth, and repeated examinations at follow up are valuable.

Blount stapling was performed in 19 patients to reduce leg length discrepancy. During the initial two years after the stapling procedure a consistent pattern of growth retardation was recognized; the more advanced the skeletal age at time of stapling, the more pronounced the growth retardation. Variations in growth rate postoperatively could be correlated to widening and transverse movements of the staples.

In stapled growth regions the intrasegmental rotations and translations between the bony epiphysis and metaphysis were analyzed. The movements

around the sagittal and transversal axes, expressing the degree of valgus-varus deformity and of re- and antecurvation were most pronounced in the proximal tibia and in children stapled at a low skeletal age.

The scintimetric analysis showed reduced tracer activity in stapled growth regions which was in good agreement with the growth rate analysis.

Insufficient staples were registered in three patients. This was early registered as an asymmetric and/or increased growth rate. Staple tip movements could be registered in two of these cases. Transverse movements inside as well as outside staple channels were recorded. The reason for loosening of the staples is most probably the transverse growth in width of the bony epiphysis and metaphysis; thus the movements of the staples are probably not due to improper surgical technique.

Scintimetry showed an initially low tracer activity, corresponding to the low growth rate registered, and later an increased activity, especially on the lateral side, corresponding to the increased growth rate.

The growth pattern after *extraction of staples* in two patients with leg length discrepancy treated by Blount stapling was evaluated. The growth rate after removal of the staples was in one case symmetric with the contralateral intact growth region and termination of growth occurred simultaneously. There were no signs of growth stimulation. In the other patient no resumption of growth appeared after removal of the staples. These findings are in agreement with those of earlier studies indicating that resumption of growth cannot be expected if staples are extracted less than 10 months prior to termination of growth in intact growth regions.

An eight year old boy developed a progressive *valgus deformity* after a Salter & Harris Type IV injury in the lateral part of the proximal tibia. As a corrective operative procedure, the insertion of staples medially was preferred. The standard radiographs including tomography showed a condensed area in the lateral part of the growth plate of the proximal tibia simulating a bony bridge. As growth was registered it was probably of osseo-fibrous origin. After medial stapling, the medial and lateral growth rates were immediately inverted. The progressive valgus and antecurvation deformity was corrected. Repeated postoperative standard radiographs revealed that the condensed area appeared displaced in diaphyseal direction. Only minor irregularities could be seen in the injured lateral part of the growth plate. The staples were removed at overcorrection and after the initial postoperative month, next to normal and symmetrical

growth was registered.

The growth dynamics following *Phemister physeodesis* were investigated. Compared to Blount stapling, growth retardation was more pronounced and growth arrest occurred earlier. In one of the two patients the scintimetric analysis was performed 17 months after physeodesis.

The scintimetry showed very low tracer activity in the operated growth region, and is valuable to check the efficiency of the Phemister procedure. The simultaneously performed RSA showed complete growth arrest.

Histological analysis of biopsies obtained from growth regions at the Phemister physeodesis provides information of the growth potential.

CONCLUSIONS

Methods have been lacking for the early and accurate recognition of growth disturbance after physeal injury and to evaluate the effect of physeodesis. In the present investigation, roentgen stereophotogrammetry (RSA) and $^{99}\text{Tc}^{\text{m}}$ MDP scintimetry were used on children in the knee region.

1. With the roentgen stereophotogrammetric technique three-dimensional growth dynamics can be determined with high accuracy and sensitivity in children. Information obtained with $^{99}\text{Tc}^{\text{m}}$ MDP scintimetry is corroborated by roentgen stereophotogrammetric analysis. The roentgen stereophotogrammetric technique yields information on longitudinal growth while scintimetry is easier to perform and provides information on a single examination.
2. Growth disturbances in the distal femur and proximal tibia following traumatic physeal injury are common. The Salter & Harris classification is of limited value for growth prediction in the knee region.
3. Following Blount stapling ;
 - a. Skeletal maturity determines the rate of primary growth retardation; the subsequent deceleration, and the ensuing basal level of growth in cases with sufficient staples.
 - b. Longitudinal growth from the growth plate and transverse growth of the bony epiphysis cause widening and transverse movements of the staples. When pronounced, this causes loosening of staples and failure to control longitudinal growth, which, when asymmetric, causes angular deformity. Increasing and asymmetric growth rates from a low basal level in the stapled growth region are early signs of insufficient staples.
 - c. The ability to resume growth after removal of staples is probably lost shortly before complete growth arrest. No evidence of growth stimulation or premature fusion is found in growth regions upon

staple extraction as long as growth is registered at extraction.

d. Angular deformity following physeal injury is corrected by unilateral physeal stapling and is an alternative to the Langenskiöld operation. A bony bridge seen on standard radiographs is probably an osseo-fibrous defect in cases with evidence of growth.

4. Following Phemister physeodesis, the growth rate decreases more rapidly than after Blount stapling. Microscopic analysis of biopsies from growth plates provides information on growth rate.

ACKNOWLEDGEMENTS

Many persons have made this study possible. I want to express my sincere gratitude to:

Lars Ingvar Hansson, guide in research and growth problems

Göran Selvik, Stefan Aronson and Yngve Naversten, who paved the methodological paths

Hanna-Stina Lundgren, Gerda Seidel, Birgitta Särgava and Kristina Persson technical assistants

Agneta Persson, Karin Nilsson and Eva Henriksson, illustrators

Jan Strömblad and Göran Eliasson, photographers

Britt-Marie Karlsson, Mona Olsson and Inger Lohmander, secretaries

Christer Hahn and Mona Olsson, lay out

Gunnar Kahlmeter, the late W. Francis Salisbury and Mikael Fahlman, supervisors of English language

The staff and the personnel of the Departments of Diagnostic Radiology and Orthopedic Surgery

My young patients, grown or still growing and their parents

Anita, Helga, Agnes and Sigrid, "never failing" family supporters

This work was supported by grants from the Swedish Medical Research Council (project 17X-02031), Alfred Österlunds Stiftelse, Folke Bernadotte Stiftelsen, Stiftelsen för Trafik och Polioskadade, Stiftelsen för bistånd åt Vanföra i Skåne, and Thorsten och Elsa Segerfalks Stiftelse.

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II

PATTERN OF GROWTH RETARDATION AFTER BLOUNT STAPLING - A Roentgen Stereophotogrammetric Analysis

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ABSTRACT

The roentgen stereophotogrammetric method has been used in 19 children, treated by stapling according to Blount for progressive leg length discrepancy. The growth plates of distal femur and/or proximal tibia were stapled. In total 31 growth regions were stapled.

Longitudinal growth rate of 25 intact growth regions of distal femur and proximal tibia was determined and correlated well to growth rates as derived from growth tables of Green and Anderson; Kemper and Sissons.

In stapled growth regions, a uniform pattern of growth retardation was found and correlated well to skeletal age. The more advanced skeletal age at time of stapling, the more pronounced and rapid initial growth retardation and the lower basal growth rate.

Significant asymmetric growth was registered in five out of 31 stapled growth regions, especially in three patients developing loosening of staples later on.

In five patients the staple tips were analyzed. Widening of staples and staple tip movement within the bony epiphysis and metaphysis were small. At low skeletal age the widening and tip movement were more pronounced than in the older cases.

In summary, the roentgen stereophotogrammetric method was used in order to analyze pre- and post-operative growth pattern and was found valuable in checking growth rates after stapling according to Blount to detect early complications such as asymmetric growth and loosening of staples. Furthermore, the movement and the deformation of the staples by the growth process could be evaluated by high precision.

INTRODUCTION

Much controversy has existed in recent decades about operative techniques to reduce leg length discrepancy in the growing child. Available operative procedures include physeodesis according to Phemister, stapling according to Blount, growth stimulation or distraction physeolysis besides osteotomies (1,7,23,27,35,37).

Stapling is the only method of temporary growth arrest (1). In clinical investigations of stapling, interest has been focused on describing frequency and types of complications after stapling. The importance of pre-operative planning, surgical technique, and post-operative follow-up has been stressed (1,8,10,12,13,16,21,22,24,26,28,36)

The response of the human growth plate and the bone after stapling has only been studied incidently (14,23,24). However, experimental data exist on the reaction of growth plates to stapling (11,18). Information is lacking about stapling at various regions, at various ages, skeletal maturity, and sex.

Roentgen stereophotogrammetry is a clinically useful method to register longitudinal growth after surgery or trauma to the growth plate (11,12,22).

This investigation is based on a study of 19 patients with Blount stapling using the roentgen stereophotogrammetric method to register the growth pattern after the stapling procedure. The children were provided with tantalum balls at stapling to permit roentgen stereophotogrammetric analysis of longitudinal and rotational movements between the epiphyseal and metaphyseal regions. The growth pattern during the initial 24 months after surgery is presented to demonstrate variations in the pattern of growth retardation. Three cases with significant asymmetric growth illustrate loosening of staples until reoperation.

MATERIAL

Nineteen children with leg length discrepancy were stapled according to Blount and investigated by the roentgen stereophotogrammetric technique at the University Hospital in Lund between 1975 and 1979. Ten were stapled both in distal femur and in proximal tibia. Only distal femur was stapled in five and only proximal tibia in six cases. The cause of the anisomelia in eight patients was a congenital hypo-/aplasia of lower leg; in three, congenital hemihypertrophy; in two, hip disorders; in two, club foot; in one, sclerodermia; in one, juvenile rheumatoid arthritis; in one, cerebral palsy; in one, traumatic growth arrest of distal femur (Table 1).

Skeletal age (SA) was assessed according to Greulich and Pyle (17). For one patient, the knee atlas of Pyle and Hoerr (29) was used to estimate skeletal age (Table 1).

The leg length discrepancy (Table 1) ranged from 20 mm to 82 mm (mean 39 mm) at the time of surgery. The final expected discrepancy at the time of skeletal maturity was calculated according to Green and Anderson (2,15) and Moseley (25). These calculations established expected future growth and the time of surgery. In general, the aim of the stapling procedure was to achieve temporary growth arrest, and the operative procedure was performed to obtain optimal correction before skeletal maturity.

At surgery Vitallium[®] staples were used according to Blount (7,34). Of the ten patients stapled in both distal femur and proximal tibia, two were operated on in a two-step procedure, with 23 and 21 months, respectively, between the operations.

TABLE 1 a) Boys stapled according to Blount

Case	Age at time of stapling yrs - mo		Diagnosis	Discrepancy at time of stapling in mm			Predicted discrepancy in mm	Region of surgery
	CA	SA		Femur	Tibia	Total		
B1	8-4	8	Congenital fibula aplasia, right	2	-54	-52	65	Prox tib, left
B2a	9-5	9	Congenital hypoplasia, right	-48	-23	-71	125	Dist fem, left
B2b	13-4	13	- " -	-15	-24	-39	25*	Prox tib, left
B3a	12-4	9	Congenital fibula aplasia, right	-19	-63	-82	125	Prox tib, left
B3b	14-1	11	- " -	-20	-60	-80	65*	Dist fem, left
B4	11-8	11	Congenital hypoplasia, right	-7	-30	-37	> 37**	Prox tib, left
B5	13-6	12	Club foot, left	-6	-15	-21	30	Prox tib, right
B6	13-8	13-6	Traumatic growth arrest dist fem, left	-24	1	-23	55	Prox tib, right
B7	15-0	14	JRA, right	-18	-9	-27	40	Dist fem and prox tib, right
B8	15-2	15	CP, left	-4	-21	-25	30	Dist fem and prox tib, right
B9	15-3	16	Slipped capital femoral epiphysis, right	-15	-9	-24	> 24**	Dist fem and prox tib, left

* Predicted discrepancy less than discrepancy at time of surgery since already provided with staples in distal femur (case 2a) and proximal tibia (case 3a)

** Preoperatively restricted to a single orthoroentgenogram and prediction accordingly not possible.

TABLE 1 b) Girls stapled according to Blount

Case	Age at time of stapling		Diagnosis	Discrepancy at time of stapling in mm		Predicted discrepancy in mm	Region of surgery
	CA	SA		Femur	Tibia		
G1	10-0	9-6	Congenital fibula-hypoplasia, left	-11	-24	-35	Prox tib, right
G2	12-5	10	Congenital fibula-hypoplasia, right	-22	-13	-35	Dist fem, left
G3	11-3	10-6	Congenital hypoplasia, right	-34	-31	-65	Prox tib and dist fem, left
G4	11-2	11	CDH, left	-17	-3	-20	Dist fem, right
G5	11-5	12	Congenital hemi-hypertrophy, right	20	14	34	Dist fem, left
G6	13-1	12	Club foot, right	-8	-22	-30	Prox tib and dist fem, left
G7	12-7	12-6	Congenital hypoplasia, left	-10	-11	-21	Prox tib and dist fem, right
G8	13-0	12-6	Sclerodermia, mainly right	-40	-53	-93	Prox tib and dist fem, left
G9	12-11	13	Congenital hemi-hypertrophy, left	17	9	26	Prox tib and dist fem, left
G10	13-7	13-6	Congenital hemi-hypertrophy, right	11	15	26	Prox tib and dist fem, right

* The functional discrepancy was found considerable due to the hip disorder. Real discrepancy difficult to assess due to deformity of the femoral capital head

** Preoperatively restricted to a single orthoroentgenogram and prediction accordingly not possible

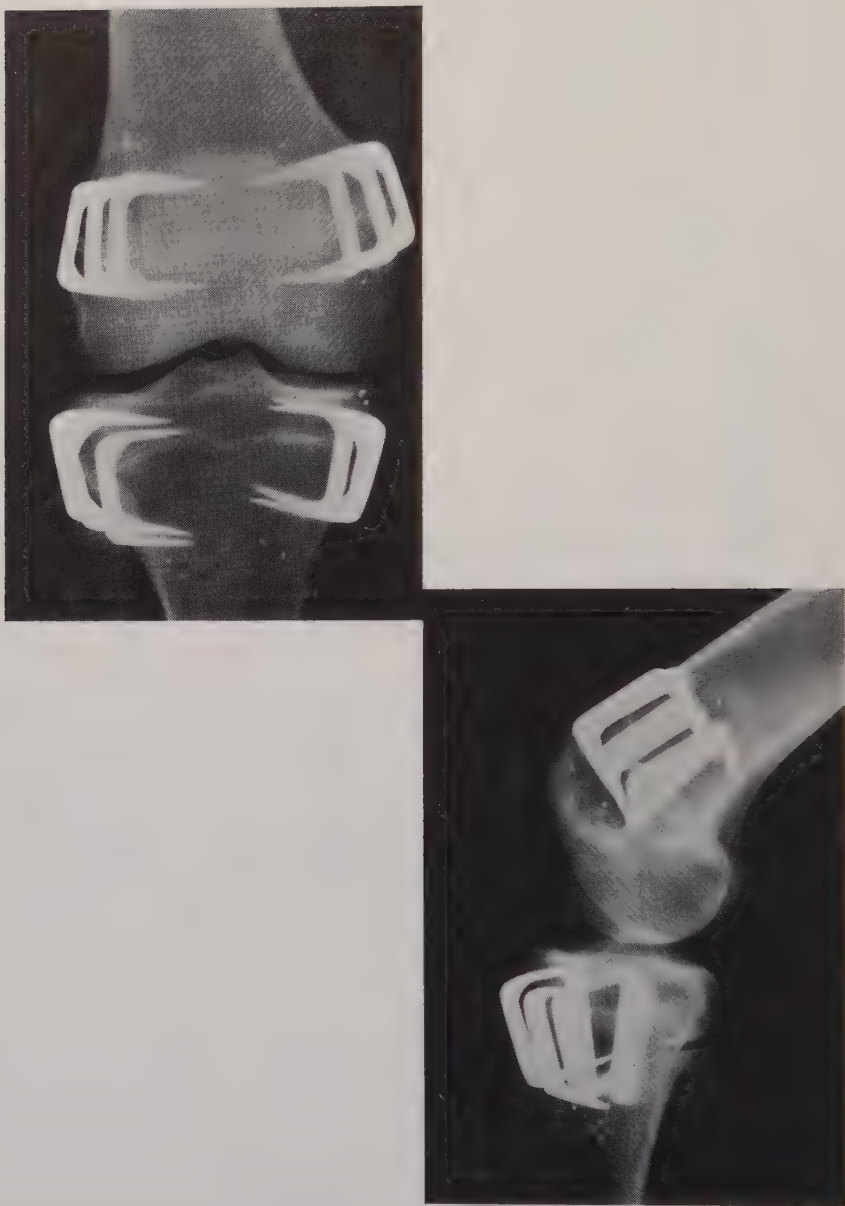


Fig. 1
Case G7. Standard radiographs of left knee eight months after stapling. a) AP view. b) Lateral view.

METHODS

The roentgen stereophotogrammetric method (32) was used for longitudinal growth registrations, kinematic analysis, and staple tip motion recordings (10). Percutaneously in local anesthesia or through the operative incision in general anesthesia, 0.5 or 0.8 mm spherical tantalum balls were implanted into the metaphysis and bony epiphysis of distal femur and proximal tibia (5). The number of balls were three to five in each segment of operated region (Fig. 1), thus permitting the use of a rigid body model concept (32). Fourteen patients had isolated tantalum balls implanted medially on each side of the growth plate on contralateral intact side; in four on the intact growth regions of operated side.

Radiography using the roentgen stereophotogrammetric technique was performed at intervals varying from one to six months, usually at three to four months intervals. Bone marrow radiation dose for a roentgen stereophotogrammetric registration proved to be about $1/2$ to $1/3$ of a conventional radiographic study (22), generally recommended at about six months intervals following stapling procedure (6,16,34).

Identification of markers was sometimes difficult, as the staple legs projected over the tantalum balls on the roentgenograms. Thus, not all markers could be identified at each registration in some patients; generally it was possible to identify at least one pair of markers medially or laterally. A slight initial instability of markers in the bone was noted in some patients during the first two weeks after the implantation of tantalum balls. A few markers were omitted due to subperiosteal localization. The three different calibration systems according to Selvik (32) were all used. Reference and patient marker images were measured in a co-ordinatograph of a precision instrument for aerial photogrammetry; the Wild Autograph A8. The spatial location of the markers in the bone was determined and the distance changes and rate of change calculated and plotted with computer graphics.

The error of method in longitudinal growth determination is 30 to 50 μm for each registration, corresponding to 1 to 2 $\mu\text{m/day}$ at monthly registration intervals (3). Error of kinematic analysis is approximately 0.2° (SE) for rotations around the three main axes (10). The biocompatibility of the markers and ethical considerations has been thoroughly discussed previously (3,30).

RESULTS

As mentioned, the analysis comprehends the initial period about 24 months after stapling procedure since at the end of this period low growth rates were registered except in cases with asymmetric growth and signs of loosening of staples.

The longitudinal growth rates of 31 stapled growth regions in 19 cases could be analyzed medially, laterally, anteriorly, and posteriorly, and presented as mean growth rates in relation to the skeletal age.

The intrasegmental rotations and translations between the bony epiphysis and metaphysis of a stapled growth region could be analyzed in 26 out of 31 regions. The analysis was performed in a computer program called KINEMA; presented are rotations around sagittal (Z) and transverse (X) axes.

The widening of staples and the movements of staple tips were analyzed in five cases, in one as distance changes between the tips; in the other four, in addition as motion relative to the markers in the bone.

Mean growth rates for distal femur and proximal tibia, as derived from growth charts of Green and Anderson (15), are plotted for comparison. Average rates for distal femur, as derived from growth rates of Kember and Sissons (19), are plotted for additional comparison, although these authors did not take skeletal age into account.

G r o w t h a n a l y s i s

1. Intact growth regions - contralateral side/operated side

Longitudinal growth of 25 intact regions is investigated during 24 months post-operatively in six boys and seven girls provided bilaterally with markers (Figs. 2a - 5a). One boy is omitted due to subperiosteal localization of the metaphyseal ball in intact proximal tibia.

Growth rates correlated well to mean growth rates derived from the charts of Green and Anderson (15) for distal femur and proximal tibia; Kember and Sissons (19) for distal femur.

Most of the intact growth regions showed an initial more or less pronounced drop in growth rate after surgery at the other side. This could not be attributed to initial instability of markers but is probably a general effect of the surgery.

Girls. In general, growth rates in distal femur (Fig. 4a) were about 40 $\mu\text{m}/\text{day}$ before eleven years (SA) and then decelerating until skeletal maturity at 14 years (SA). Two patients with hypoplasia fibulae showed lower growth rates compared with patients considered normal. However, two of the girls, Cases G4 and G6 (considered normal) showed low growth rates similar to the patients with hypoplasia.

The growth pattern for proximal tibia (Fig. 5a) is consistent with the growth pattern in distal femur but the growth rates were lower. One girl, Case G3, showed a varying pattern, during the initial 18 months, increasing from 7 $\mu\text{m}/\text{day}$ to 13 $\mu\text{m}/\text{day}$ and then decelerating until maturity at SA approximately 13 years.

Boys. Growth rates in distal femur (Fig. 2a) in case B4 (hypoplasia) and Case B7 (normal) were both in agreement with Green and Anderson and with Kember and Sissons. Case B3 and B7 (hypoplasia) showed deceleration at lower ages.

The growth diagram of proximal tibia (Fig. 3a) showed growth rates before 14 years (SA) at 30 $\mu\text{m}/\text{day}$ and in Case B2 (hypoplasia) even at a larger rate, approximately 40 $\mu\text{m}/\text{day}$. Deceleration starts at SA approximately 13 to 14 years.

Correspondence to rates derived from the growth charts of Green and Anderson was good except for Case B3 (hypoplasia) where growth rate fell from 25 $\mu\text{m}/\text{day}$ at SA approximately 12 years.

The termination of growth occurred six to twelve months earlier in proximal tibia than in distal femur in the girls as well as in boys.

2. Stapled growth regions

a. Longitudinal growth - period of growth retardation and basal growth

A consistent pattern of growth retardation is recognized except in three cases during the initial 24 months post-operatively. Some irregularities seen as asymmetric growth are noted, especially after stapling at low skeletal age and in proximal tibia (Figs. 2b - 5b).

The primary rapid growth retardation and subsequent deceleration showed in general a similar pattern but on different levels with increasing skeletal age. The more advanced skeletal age at the time of stapling, the more pronounced the primary instant and secondary slow growth retardation and also lower basal growth rate, corresponding to low growth rates seen as plateau values (Fig. 2 b - 5b).

Three groupings of skeletal age are chosen in boys and girls, representing somewhat different patterns of growth response after stapling.

At SA below ten years (girls) and twelve years (boys), there is an initial growth 5 to 10 $\mu\text{m}/\text{day}$. A different pattern of growth is seen in one boy (Case B1) stapled in proximal tibia at

SA eight years (Figs. 3b and 6a). A similar pattern with eventually loosening of staples was registered in two other boys (Case B2a and Case B4).

At SA ten to twelve years (girls, Figs. 4b and 5b) and twelve to 14 years (boys, Figs. 2b and 3b) in general there is a more pronounced and more rapid growth retardation.

Basal growth was attained in shorter time the more advanced SA at time of stapling. The pattern of growth retardation was more uniform in distal femur than in proximal tibia. In one case (Case G3, Fig. 5b) the growth rate did not decrease to low basal growth during initial 24 months after stapling, but on the other hand, no loosening of staples has been registered during follow-up. During the third year the growth rate decreased to low levels close to zero.

Girls at SA above twelve years and boys above 14 showed growth rates immediately after stapling reduced to below $5\text{ }\mu\text{m/day}$. The more advanced SA, the more pronounced initial growth retardation. During the following two to six months, the growth rates decelerated rapidly to low basal levels or complete growth arrest.

b. Longitudinal growth - asymmetric growth

Asymmetric growth after stapling is possible to register in terms of longitudinal growth rates medially, laterally, anteriorly, and posteriorly. However, the angular deformity emerging as a result of asymmetric growth, is better presented in terms of rotations around sagittal (Z) and transverse (X) axes in the KINEMA analysis.

Various amounts of progressive asymmetric growth were found early and/or late post-operatively and resulted in angular deformity.

This investigation showed pronounced asymmetric growth and progressive angular deformity in one boy stapled in distal femur and two boys stapled in proximal tibia. The boy (Case B2a)

Growth rate
 $\mu\text{m/day}$

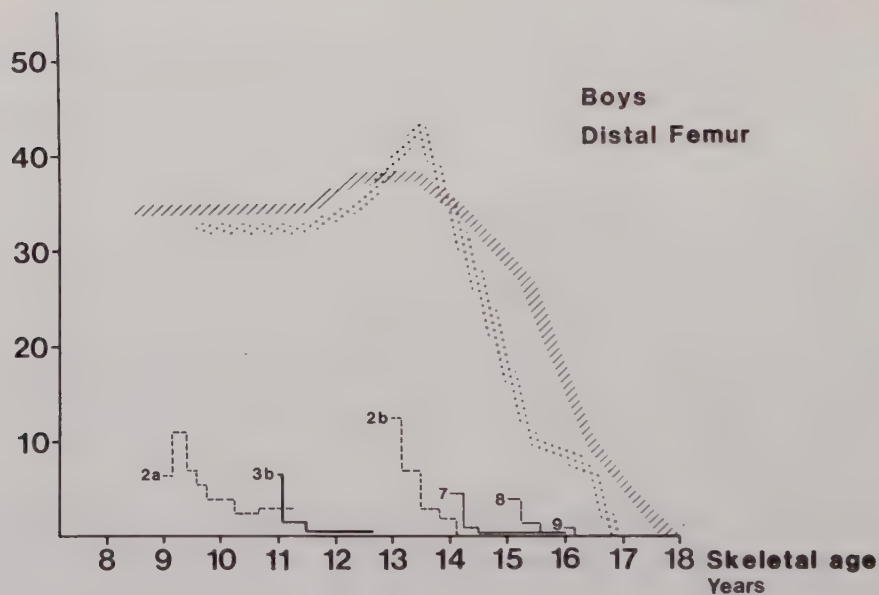
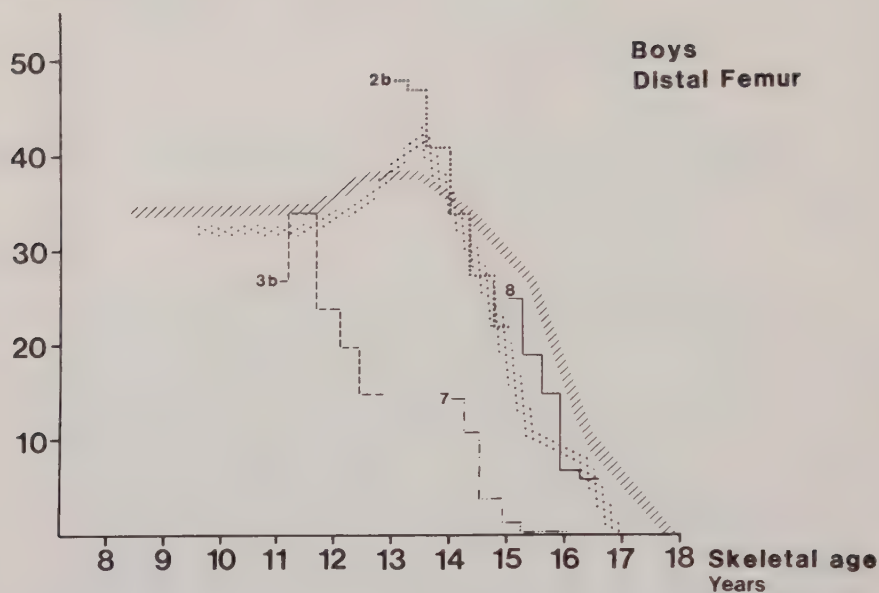


Fig. 2

Growth diagrams. Boys, distal femur.

a) Intact growth regions. b) Stapled growth regions.

/// Calculated values from Kemper and Sissons (19)

.... Calculated values from Green and Anderson (15)

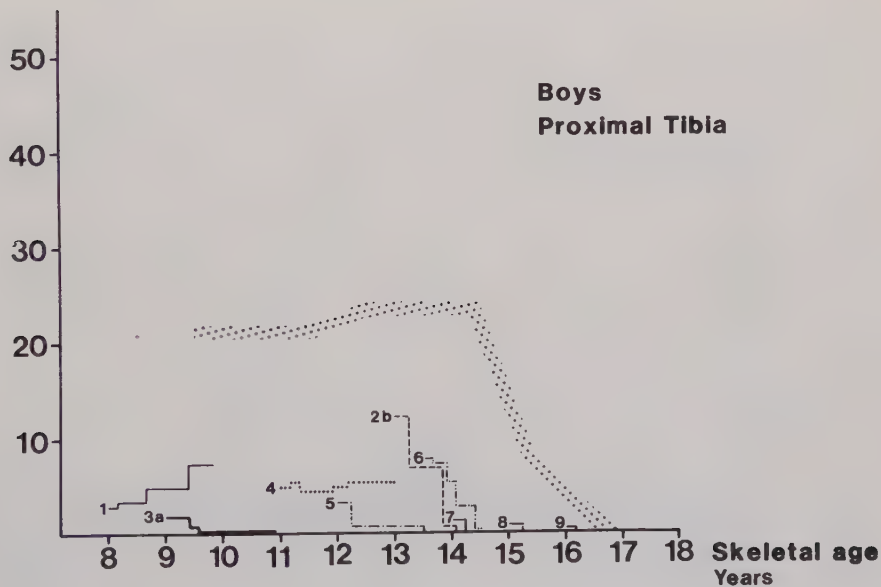
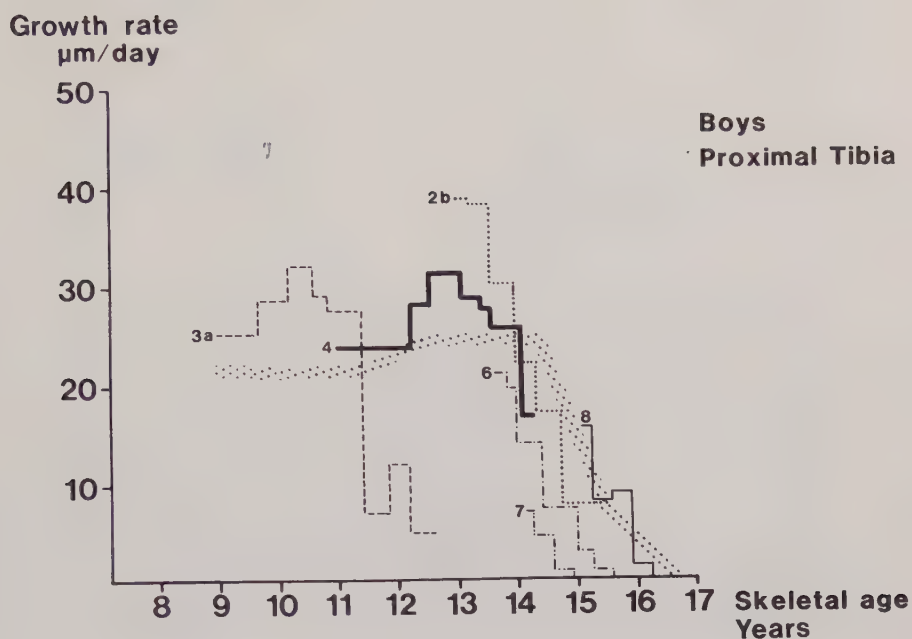


Fig. 3
Growth diagrams. Boys, proximal tibia. (For symbols see Fig. 2.)
a) Intact growth regions. b) Stapled growth regions.

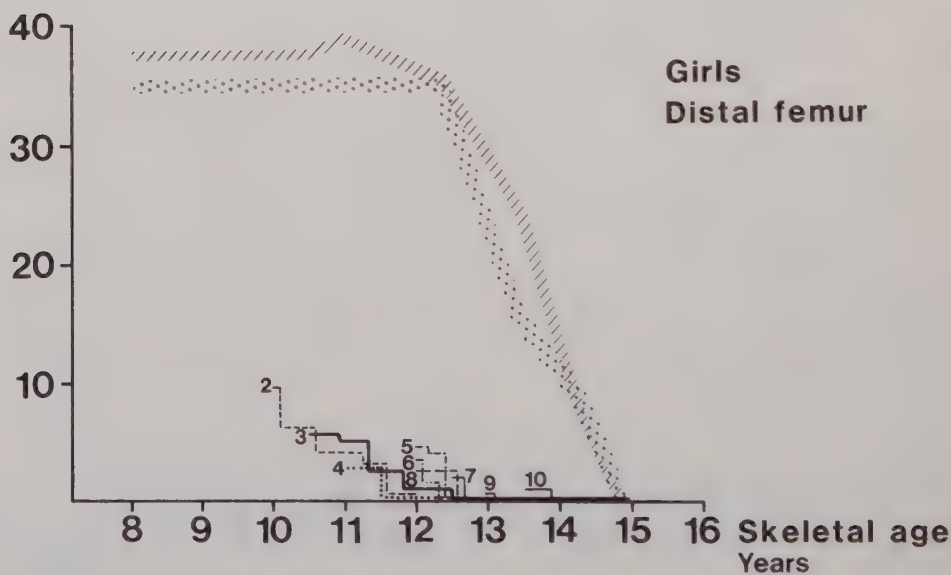
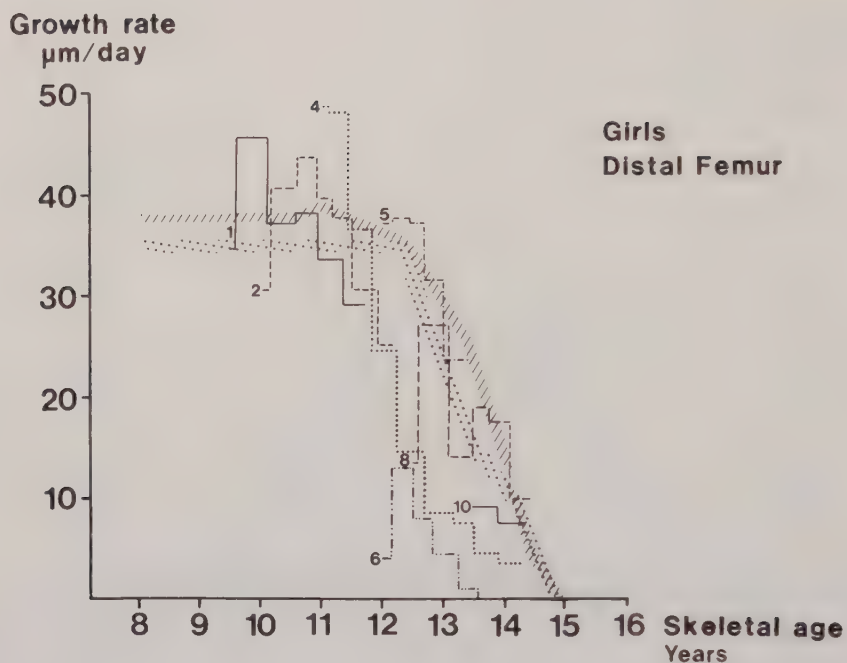


Fig. 4
Growth diagrams. Girls, distal femur. (For symbols see Fig. 2.)
a) Intact growth regions. b) Stapled growth regions.

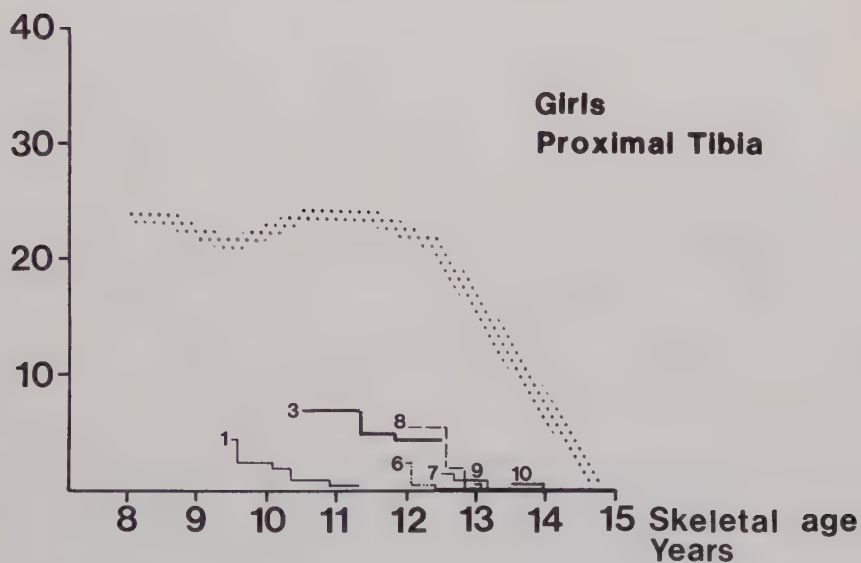
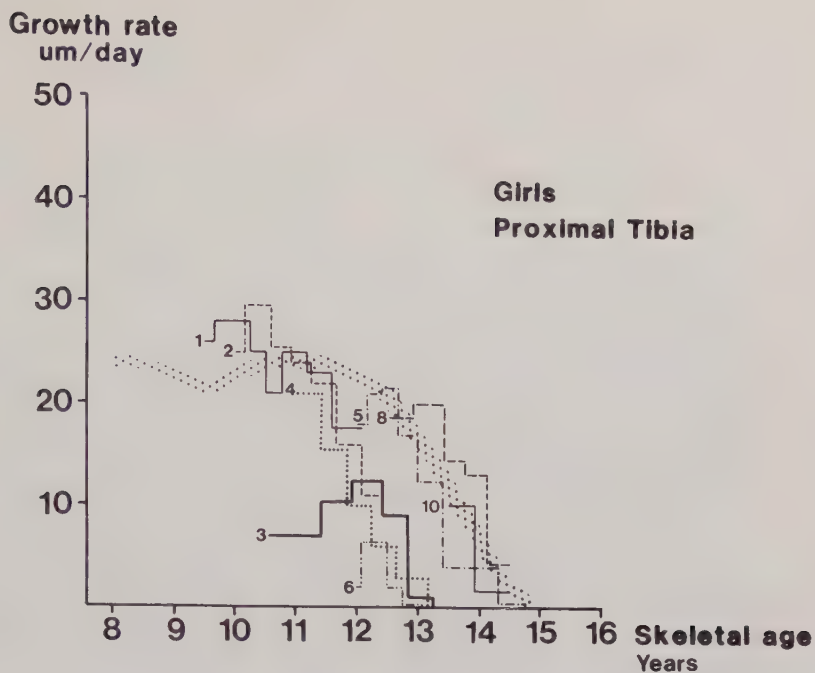


Fig. 5
Growth diagrams. Girls, proximal tibia. (For symbols see Fig. 2.)
a) Intact growth regions. b) Stapled growth regions.

stapled in distal femur is thoroughly investigated and discussed in a previous study (10).

A boy (Case B1) stapled in proximal tibia at SA eight years showed early appearing asymmetric growth but increased within the ensuing 24 months (Fig. 6a). Growth rates were initially small at about $3\text{ }\mu\text{m/day}$, slightly higher laterally than medially. During the subsequent period of investigation, increasing growth rates, laterally about $13\text{ }\mu\text{m/day}$ and medially about $10\text{ }\mu\text{m/day}$, resulted in a progressive angular deformity, kinematic analysis showed the accumulated degree of varus deformity amounting to 11.5° at time of reoperation. Replacement of staples was performed 32 months after initial stapling procedures (Fig. 6b).

Case B2a, stapled in distal femur at SA nine years, showed an initial period of a slightly asymmetric growth and decreasing growth rates to low levels (Fig. 7a). The subsequent period of basal growth at about $4\text{ }\mu\text{m/day}$, slightly higher laterally than medially, was followed by a late increment of asymmetric growth with increasing growth rates especially pronounced laterally. Loosening of staples was found, and the reoperation was performed 47 months after initial stapling. Simultaneously, staples were inserted in proximal tibia. Kinematic analysis showed the accumulated growth degree of varus deformity amounting to 4.3° at time of reoperation. The degree of recurvatum amounted to 6.9° (Fig. 7b).

A boy, (Case B4) stapled in proximal tibia at SA eleven years showed early appearing asymmetric growth resulting in a progressive angular deformity (Fig. 8a). Growth was initially medially at low rate $1\text{ to }2\text{ }\mu\text{m/day}$, and laterally at $7\text{ }\mu\text{m/day}$, increasing to $12\text{ }\mu\text{m/day}$. Replacement of staples was done 37 months after initial stapling when kinematic analysis showed the accumulated degree of varus deformity amounting to 9.0° and the degree of recurvatum amounting to 13.4° (Fig. 8b).

c. Staple widening and tip motion

The gap distance of the staple, expressing staple widening in the Y-direction was studied in six cases with an accuracy of

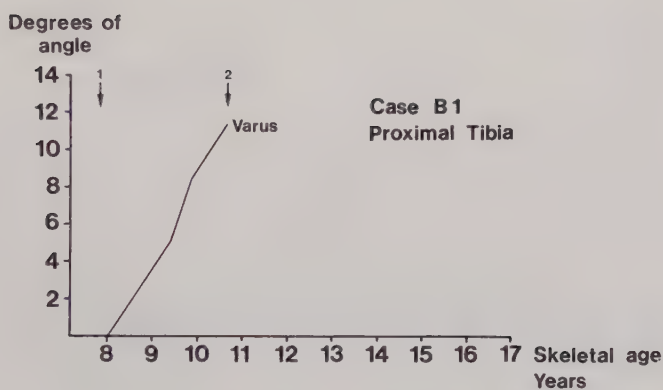
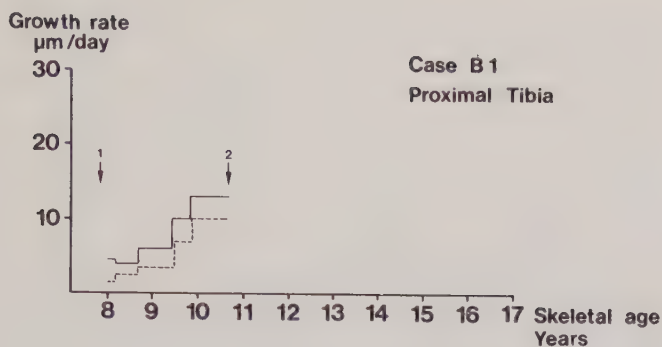


Fig. 6

Case B1. Stapled growth region, proximal tibia.

a) Growth diagram. 1) Stapling according to Blount.
2) Reoperation. Full line represents lateral growth;
interrupted line medial growth.

b) Kinematic analysis of metaphysis in relation to bony
epiphysis. Rotation about sagittal axis.

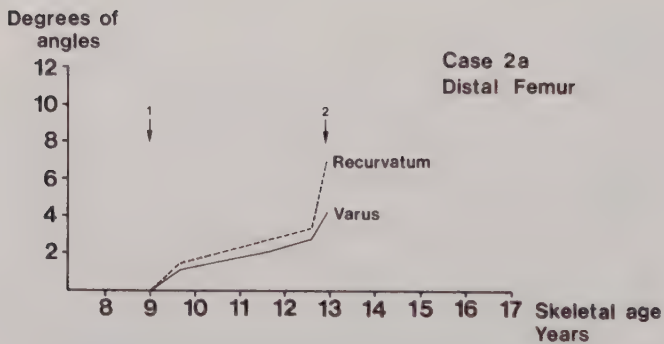
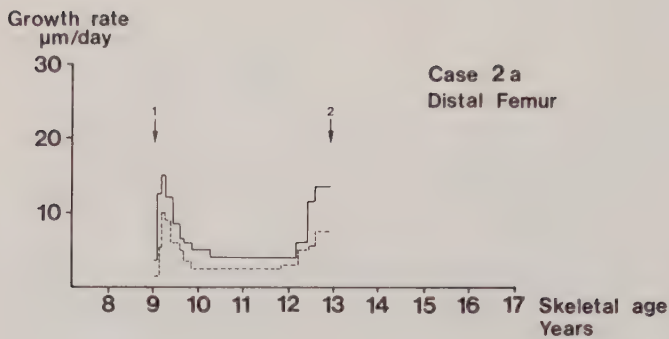


Fig. 7

Case B2a. Stapled growth region, distal femur.

a) Growth diagram. 1) Stapling according to Blount. 2) Reoperation. Full line represents lateral growth; interrupted line medial growth.

b) Kinematic analysis of bony epiphysis in relation to metaphysis. Full line represents rotation about sagittal axis; interrupted line rotation about transverse axis.

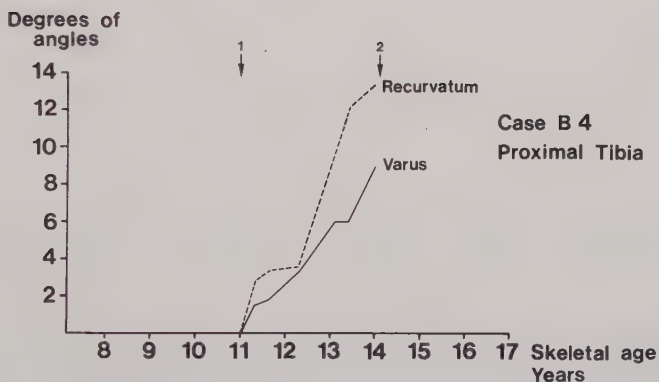
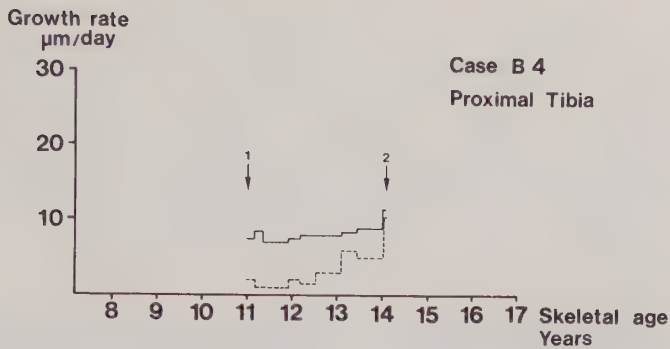


Fig. 8

Case B4. Stapled growth region, proximal tibia.

a) Growth diagram. 1) Stapling according to Blount. 2) Reoperation. Full line represents lateral growth; interrupted line medial growth.

b) Kinematic analysis of metaphysis in relation to bony epiphysis. Full line represents rotation about sagittal axis; interrupted line rotation about transverse axis.

0.1 to 0.2 mm (Table 2). The widening varied in between the separate staples and was more pronounced for the medial group in distal femur and proximal tibia. Even in cases with asymmetric growth and signs of loosening of staples (Case B2a and Case B4) significant more pronounced widening of medial staples were registered in spite of evidence of insufficiency especially laterally.

Epiphyseal and metaphyseal tip motion was assessed in relation to the reference markers in respective segment in five cases (Table 3). The peripheral (transversal) translations of medial and lateral staple tips were in most cases small. The epiphyseal tips moved more than the metaphyseal tips moved centripetally, indicating tilting of the staples as the epiphyseal staple tips moved in a centrifugal direction. The longitudinal translations were in most cases small. The epiphyseal tips moved more toward the growth plate indicating movements within the preformed channels. Analysis of epiphyseal tip motion was not possible in one case (Case B5) due to the configuration of rigid body model within the epiphysis.

The displacements of the tips are presented in Case B4 as the orthogonal projection on the XY (frontal) co-ordinate plane using computer graphics (Fig. 9).

Tip motions are based on recordings on three occasions. The displacements vectors are presented as arrows indicating the movement of the tips in relation to a co-ordinate system fixed in the epiphysis. The markers in the epiphyseal region represent such a co-ordinate system, and the calculated movements are in principle independent of the actual positions of the markers in the bone. Translation of center of gravity (c.g.) and lines through the c.g. show the varus angulation of the metaphysis. All tips moved in a caudally direction and more pronounced laterally. The peripheral movement was higher medially than laterally.

TABLE 2 Increase of distance in mm between tips of separate staples during 24 months following stapling.

M = medial, L = lateral, 1 = anterior, 2 = middle, and 3 = posterior staple.

	Tibial staples				Femoral staples	
	B3	B4	B5	B9	B2a	G5
Days	1385	1085	760	1030	825	835
M 1	0.7	3.6	1.7	0.0	3.8	1.0
M 2	1.4	3.5	-	0.0	2.6	1.3
M 3	2.5	5.3	2.2	-	3.2	1.5
-----					-----	
Mean	1.5	4.1	2.0	0.0	3.2	1.3
L 1	0.1	1.9	0.7	0.1	3.9	0.5
L 2	0.8	5.3	1.9	0.4	2.4	0.3
L 3	1.8	0.4	-	0.5	2.2	0.9
-----					-----	
Mean	0.9	2.5	1.3	0.3	2.8	0.6

TABLE 3 Translations for tips of staples in mm during about 24 months. Translations are given along the X-axis (transversal) where a minus sign denotes motion toward the center of the bone i.e. centripetal direction, and along the Y-axis (longitudinal) where a minus sign denotes motion away from the growth plate. Metaphyseal tips (m) are given in relation to the metaphysis, epiphyseal tips (e) are given in relation to the epiphysis.

Tip	Stapled region	Proximal Tibia						Distal Femur			
		B3		B4		B5		B2a		G5	
		X	Y	X	Y	X	Y	X	Y	X	Y
	Case	1385		1084		760		1400		835	
	Transl movement										
	Days	1385		1084		760		1400		835	
M 1	m	-0.1	0.5	0.4	0.1	0.1	0.7	4.8	0.0	0.5	0.7
	e	0.5	-0.2	8.7	0.3	-	-	5.1	1.2	0.8	-0.1
M 2	m	-0.2	0.2	0.6	0.3	-	-	7.7	-0.9	1.3	1.3
	e	0.4	-0.1	4.9	1.9	-	-	11.4	5.0	1.6	0.0
M 3	m	-0.1	-0.1	0.6	0.4	1.2	-0.4	4.1	1.6	1.5	1.0
	e	0.5	0.2	6.6	2.1	-	-	9.7	5.7	1.8	0.6
L 1	m	-0.1	0.3	11.1	5.2	0.2	1.5	4.2	0.8	0.7	0.0
	e	-0.8	0.2	4.2	3.8	-	-	10.2	3.0	0.3	0.0
L 2	m	0.2	0.1	4.8	-0.1	-0.5	0.8	7.8	1.1	0.9	0.1
	e	-0.4	0.1	0.5	0.8	-	-	10.4	2.3	0.6	0.7
L 3	m	0.3	-0.1	5.9	1.4	-	-	8.7	0.3	0.8	0.8
	e	-0.2	0.0	0.4	4.1	-	-	13.8	7.4	0.5	0.5

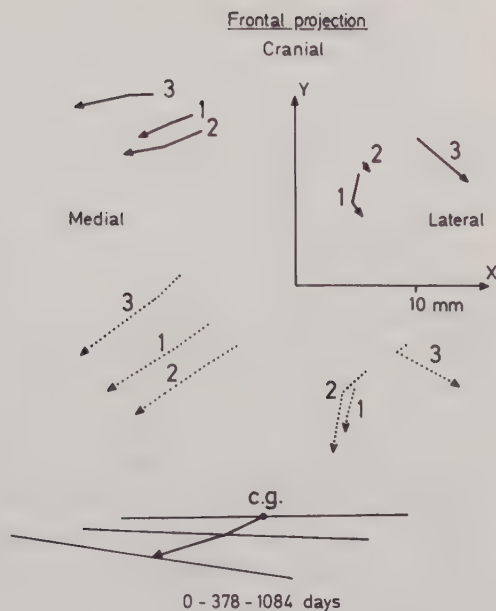


Fig. 9
Case B4. Movements of staple tips in relation to the bony epiphysis. Proximal tibia, frontal projection. Full lines represent epiphyseal tips; dotted lines represent metaphyseal tips. 1) anterior, 2) middle, 3) posterior staple; c.g., center of gravity of metaphyseal balls. Lines through c.g. represent varus angulation of the metaphysis.

DISCUSSION

Information is still lacking about the exact mechanisms of growth retardation and arrest in children after stapling according to Blount. Methods for sensitive longitudinal growth determinations of intact or operated growth regions in children have previously not been available. The improvement of the roentgen stereophotogrammetric method has resulted in a very accurate method of studying growth problems (3,11,12,22,33).

This investigation, using the sensitive and accurate roentgen stereophotogrammetric method, (3,9,10,20,32) shows the pattern of growth retardation related to skeletal age and growth regions thus elucidating some of the previous unsettled questions regarding remaining growth and efficiency of staples.

Information of growth pattern of the short leg is not only of importance in predicting final discrepancy, but also as correlation for the effect on longitudinal growth after stapling. Growth rates of intact growth regions in distal femur and proximal tibia show rather good correlation with rates derived from growth tables, as found in other investigations (15,19). Normally the growth rates decelerate continuously at puberty and the deceleration curves are rather parallel in distal femur and proximal tibia. Termination of growth is accomplished at SA approximately 14 years (girls) and 16 years (boys) in proximal tibia and six to twelve months later in distal femur. This agrees with previous studies (15,19).

In evaluating growth response after the stapling procedure, consideration to growth rates of both legs and skeletal maturity must be essential. Longitudinal growth rate determination may provide more accurate information of skeletal maturity even if it is pointed out (14) a discrepancy between skeletal age assessed from radiographs of the hand and wrist and those from the knee.

This investigation supports the assumption that growth arrest after stapling is a gradual process of growth deceleration (6,16,26). The general pattern of growth retardation depends on the skeletal maturity. This distinction is based on the instant primary growth retardation, how rapidly the levelling out to basal level occurs, and the level of basal growth.

Pattern of growth retardation at young age (SA below ten years for girls and twelve for boys) shows growth, after initial retardation, normally settling at a basal growth at slow rate about 5 $\mu\text{m}/\text{day}$.

This pattern of growth retardation and basal growth (in the literature mentioned as remaining growth) is noted by others with various explanations. Mc Gibbon (22) thought that stapling caused an early acceleration of growth until compression occurred, but this has not been found in this investigation as the growth rate in all stapled regions has been far below the normal or the contralateral growth region.

A temporary increase of growth rate was found in one boy (Case B2a) stapled in distal femur at SA nine years. However, this increase, far below the normal growth rate, during approximately six months was preceded by an initial marked retardation immediately post-operatively.

Nordentoft (26) claimed that remaining growth corresponds to insufficient growth arrest and found a several times higher incidence of insufficiency of staples on the tibia than on the femur. The stage of biological development is likely to influence the frequency of insufficient growth retardation after stapling. This agrees with others (7,16,28) who found remaining growth especially pronounced after stapling in proximal tibia, but who, unlike Nordentoft, attributed their findings to difficulties in proper insertion of the staples, to the construction of the staple itself, and to the tubulation and resorption of the metaphysis (6,36).

As pointed out by Blount (6), stapling in proximal tibia is technically more difficult because of the asymmetric and conical shape of the tibia. This is especially true for the lateral aspect of the bone and explains why, as found in this investigation, varus and recurvation deformity were frequently recognized.

Increasing growth rate indicate early signs of insufficient staples as seen in all three cases with asymmetric growth. In Case B1 the increasing growth rate is present during the first six months following initial deceleration after the stapling procedure. Case B2a shows a different pattern of initial deceleration. Following the primary instant marked retardation of growth, deceleration continuous from a somewhat higher rate and is levelling out on a low basal level. This may indicate an early sign of insufficiency, even if the slow basal growth during approximately 24 months represents the normal mechanism of growth retardation by stapling, until finally the increasing growth rate indicates loosening of staples.

Thus, asymmetric growth might develop late, after a period of fairly symmetric growth at low basal level (Case B2a), or will be obvious almost immediately after stapling (Case B4) and results in progressive angular deformity. Asymmetric growth might likewise develop in a progressive slowly increasing deformity (Case B1).

The finding that the growth retardation is more pronounced and faster approaching growth arrest at more advanced skeletal age is obvious. Theoretically stapling at younger age would result in more rapid retardation, as the gap between the staple legs would be expanded in shorter time as a result of the higher growth rate. This process is theoretically delayed when growth rate is slower. However, this does not agree with the findings. The explanation is probably that the staples move peripherally in relation to the bone and that the gap between the staple tips is widened. As found previously (10) the tips move in the channels and/or cut through the bone. At more advanced skeletal age, the growth rate is lower; on the other hand, the bone fixation of staples is more

firm, and the tendency of sliding in the channel and cutting through bone is less prominent.

The total accumulated growth during 24 months after stapling decreases significantly with skeletal age (Table 4). This agrees with the finding that growth continues at slow basal level, approximately 5 to 10 $\mu\text{m}/\text{day}$, when stapling is performed at younger skeletal age. This basal level will approach growth arrest and the initial depression of growth will be more pronounced the more advanced the skeletal age at time of surgery.

Widening and extrusion of staples have been related to remaining growth after stapling (7,16,28) or "caused by the stress of the arrest of growth" (12). Blount (7) stated that there might be some slipping and drifting of the staples; he also concluded that it would be desirable to allow some slipping so as to maintain viability of the growth plate. Continuous growth at basal level prevents growth arrest and is not the result of failure of the staples to control growth (10). Green and Anderson (16) examined the widening and extrusion of staples and noted up to 1.5 cm of widening between the tips of the staple legs. This widening was found to take place mainly during the first year after surgery. This investigation notes a similar widening correlated to the skeletal age.

Blount (6) attributed extrusion and bending of staples in tibia mainly to errors in operative technique and tubulation of proximal tibia. Inadequate position of staples must be an important factor as explanation for extrusion of staples. Furthermore, in proximal tibia and also in distal femur, the growth in width of the epiphysis is probably another important factor. Scheller (31) investigated the growth of the bony epiphyses of the knee. He expressed the growth in width as mean epiphyseal width index and related this to age. He found a marked difference between growth in width in femur and tibia after age seven years (boys) and five years (girls). The investigation showed that the proximal tibial epiphysis grows in width more and at higher age compared to the distal femoral epiphysis. This provides evidence for the

TABLE 4 a) Boys. Accumulated growth and kinematic analysis during 24 months following stapling

Case	Follow-up days	Growth dist femur (mm)			Growth prox tibia (mm)			Total Gain	Rotational movements (degrees) ¹		
		Intact side	Stapled side	Gain	Intact side	Stapled side	Gain		Femur	Tibia	
									X ¹	Z ²	X ¹ Z ²
B1	721				13.2	4.3	8.9				6.1 8.4
B2a	819		3.8					-1.8	1.9		
B2b	746	26.3	3.2	23.1	18.8	3.4	15.4	38.5	-0.6	0.5	-7.7 0.7
B3a	685				17.6	0.5	17.1				2.4 0.6
B3b	609	14.9	0.2	14.7	8.6	0.2	8.4	23.1	0.2	0.9	-1.1 1.6
B4	768				19.8	2.9	16.9				-9.3 6.0
B5	760					1.4					* *
B6	728	0**	0.7***	-0.7	7.4	1.1	6.3	5.6			1.4 0.6
B7	618	3.6	0.5	3.1	1.5	0.2	1.3	4.4	-0.6	-0.2	-4.0 0.1
B8	707	8.3	0.7	7.6	3.7	0.2	3.5	11.1	1.7	0.5	-2.9 0.3
B9	743		0.1			0			-0.9	-0.4	* *

¹ Rotational movements about transverse (X) and sagittal (Z) axes. X = recurvation, -X = antecurvation, Z = varus, -Z = valgus.

* Configuration of rigid body model not optimal thus not permitting kinematic analysis of space co-ordinates.

** Posttraumatic growth arrest. *** Physiodesis according to Phenister.

TABLE 4 b) Girls. Accumulated growth and kinematic analysis during 24 months following stapling

Case	Follow-up days	Growth dist femur (mm)		Growth prox tibia (mm)		Total Gain	Rotational movements (degrees) ¹ of stapled growth regions		
		Intact side	Stapled side	Gain	Intact side	Stapled side	Femur	Tibia	Z
G1	699	27.0	27.6	-0.6	17.4	1.1	16.3	15.7	-3.5 -1.9
G2	706	26.7	2.8	23.9	16.4	17.1	-0.7	23.2	-5.8 0
G3	661		2.4		5.9	4.2	-1.7	0.8	2.4 -7.1 -0.2
G4	659	20.7	0.4	20.3	8.4	8.6	-0.2	20.1	-5.1 0.5
G5	639	18.2	1.0	17.2	9.5	10.9	-1.4	15.8	-3.6 -0.8
G6	663	3.4	0.3	3.1	1.1	0.3	0.8	3.9	-0.4 1.8 *
G7	763		0.3			0.4		-1.9	-0.6 -1.9 0.1
G8	677	12.5	0.9	11.6	10.1	1.0	9.1	20.7	-1.9 -0.2 -2.6 -1.1
G9	706		0.1			0.2		-0.3	0.8 -2.3 -0.2
G10	892	3.2	0.6	2.6	4.2	0.5	3.7	6.3	* 1.8 -0.1

¹ Rotational movements about transverse (X) and sagittal (Z) axes. X = recurvation, -X = antecurvation, Z = varus, -Z = valgus.

i = Intact growth region of stapled side.

* Configuration of rigid body model not optimal thus not permitting kinematic analysis of space co-ordinates.

susceptibility of staples to extrude in proximal tibia both before and after eight years of age.

The most favourable time for stapling, according to previous and this investigations, is to staple above eight years of age because of the risk of failure due to the growth mechanism at younger age. Stapling can be used for temporary growth arrest, but it is also performed with the intention of leaving staples until growth has ceased. The proper time for stapling depends on the skeletal age, estimated remaining growth of the short leg, and the amount of discrepancy and predicted height of the patient.

In conclusion:

The post-operative growth pattern following stapling correlates well to skeletal age and atypical growth pattern is present in cases with asymmetric growth. The roentgen stereophotogrammetric technique is valuable for the pre-operative evaluation of growth rates in children with leg length discrepancy and has proved suitable to check growth after stapling and in early detection of complications, such as loosening and extrusion of staples. Furthermore, the technique permits evaluation by high precision of movements and deformation of staples by the growth process.

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IV

A ROENTGEN STEREOPHOTOGRAMMETRIC ANALYSIS OF GROWTH PATTERN AFTER EXTRACTION OF STAPLES

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ABSTRACT

The roentgen stereophotogrammetric analysis (RSA) was used to register growth after extraction of staples in cases with unequal leg length treated by stapling. Two boys stapled in distal femur and/or proximal tibia were investigated. The staples were extracted 2-3½ years after stapling when skeletally below or approximately at 15 years of age. The growth rate, after the removal of staples, was in one case symmetric to contralateral intact growth region and termination of growth occurred simultaneously. In the other case no resumption of growth appeared after the removal of the staples.

The investigation demonstrates the value of RSA for longitudinal growth rate analysis in stapled and non-stapled growth regions. The ability to resume growth after removal of staples is probably determined by the basal growth level, and probably lost following complete growth arrest after stapling. Provided basal growth is present, normal growth resumes after removal, independent on for how long the staples are left in situ.

INTRODUCTION

Introducing the stapling procedure in the treatment of leg length discrepancy, Blount & Clark (1949) originally used staples with the intention to retard growth temporarily. Complete growth arrest was not intended as it might cause premature closure of the growth plate.

Resumption of growth following extraction of staples was considered the main advantage of stapling (Trias et al. 1961, McGibbon et al. 1962) compared to epiphyseodesis according to Phemister (1933).

Interest was focused on for how long staples could be left in situ with resumed growth after removal (Blount & Clarke 1949, Goff 1960, Nordentoft 1964, Frantz 1971) and on whether or not premature fusion occurred in stapled growth regions, provided the growth plate was radiographically open at the time of extraction. The ability of the growth plate to resume growth following a period of stapling varied, and was found difficult to predict by standard radiographs (Blount 1971).

In order to evaluate growth, following extraction of staples, the growth pattern of previously stapled growth regions was investigated by the roentgen stereophotogrammetric technique. Roentgen stereophotogrammetric analysis (RSA) permits registration of longitudinal growth with high accuracy (Selvik 1974, Aronson 1976, Bylander et al. 1981a,b, Kärrholm et al. 1982).

MATERIAL AND METHODS

Two boys, stapled earlier because of unequal leg length, were investigated with the roentgen stereophotogrammetric technique (RSA) following extraction of staples in proximal tibia (Case 1) and distal femur and proximal tibia (Case 2). Skeletal ages (SA), assessed according to Greulich & Pyle (1950) at time of surgery were below or approximately 15 years of age.

Determination of the longitudinal growth rate was performed using the RSA. Peroperatively at stapling procedure (Case 1) or at extraction of staples in distal femur, 9 months after extraction of staples in proximal tibia (Case 2), 0.5 mm tantalum balls were implanted bilaterally in proximal tibia and/or distal femur proximally and distally to the growth plate. Examinations with RSA were performed at varying intervals ranging from 4 to 12 weeks. Two different calibration systems according to Selvik (1974) were used. The two-dimensional images of reference and patient markers were measured in an instrument for aerial photogrammetry, a Wild Autograph A8. The computer calculations for spatial location and the changes in distance of the markers in the bone were performed on a Univac 1100/80 at Lund University Computing Centre. The error of the method at each registration is 30-50 μm corresponding to 1-2 μm a day at monthly examination intervals (Aronson 1976, Bylander et al. 1981b, Kärrholm et al. 1982).

CASE REPORTS AND RESULTS

Case 1. A boy, with a progressive leg length discrepancy since early childhood with club foot and shortening of left leg, had his right proximal tibia stapled at chronological age (CA) 13 years and 6 months (SA approximately 12 years). At this time the left leg was 2.1 cm shorter than the right. At surgery 0.5 mm tantalum balls were implanted medially and laterally in right proximal tibia. Standard radiographs postoperatively showed staples in good position. The efficiency of staples was checked by clinical examinations and RSA at intervals ranging from 4 to 12 weeks. Clinical examinations revealed equal leg length 38 months later (SA approximately 15 years) and examination with orthodiagraphic radiographs showed an overcorrection of 0.8 cm. Standard radiographs showed open growth plates of intact left distal femur and proximal tibia. Extraction of staples was then performed and single markers of 0.5 mm tantalum balls were implanted in the bony epiphysis and metaphysis of distal femur bilaterally and

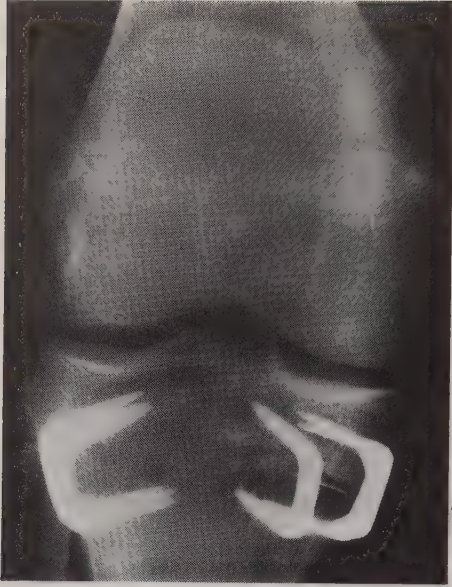


Fig. 1 a and b. Case 1. Standard radiographs of right knee at time of extraction of staples. a) AP view; b) lateral view.

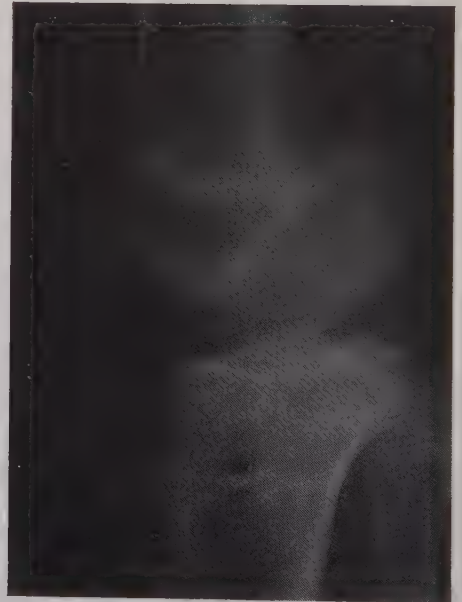


Fig. 2 a and b. Case 1. Standard radiographs of right knee after extraction of staples. a) AP view; b) lateral view.

in left proximal tibia. Standard radiographs showed laterally local fusion of the physis in stapled right proximal tibia and open growth plate in right distal femur (Figs 1 and 2). The boy was investigated for 22 months, after which he sustained a diaphyseal fracture of the right femur. Further examinations were not performed as he was treated by intramedullary nailing and his growth regions were fused at that time.

A. Longitudinal Growth Rate - Distal Femur

1. Stapled side - non-stapled growth region

The growth diagram of the right distal femur (Fig. 3a) showed that the growth rate was 10 $\mu\text{m}/\text{day}$ during the initial month and then 13 $\mu\text{m}/\text{day}$ during 8 months. The growth rate was decelerating to termination of growth approximately 12 months after implantation of the tantalum balls. The accumulated growth after the total period of investigation amounted to 3.1 mm.

2. Non-stapled side

The growth diagram of the left distal femur (Fig. 3a) showed that the growth rate was initially 15 $\mu\text{m}/\text{day}$ and subsequently decelerating to termination of growth, approximately 8 months after implantation of the markers. The accumulated growth was 2.2 mm during the period of investigation.

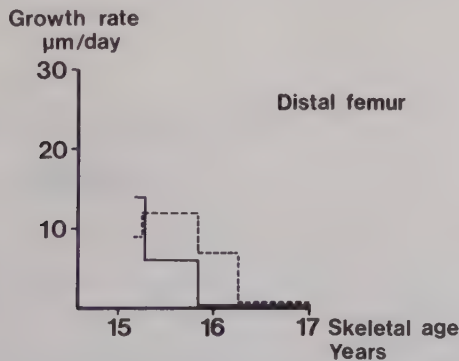


Fig. 3 a. Case 1. Growth diagram. Distal femur. Solid lines represent non-stapled left side. Interrupted lines represent stapled right side. B = Blount stapling; E = Extraction of staples.

B. Longitudinal Growth Rate - Proximal Tibia

1. Stapled side - stapled growth region

The growth diagram (Fig. 3b) showed growth retardation in right stapled proximal tibia following the stapling procedure. The growth rate was immediately reduced to below 5 $\mu\text{m}/\text{day}$. During the following 18 months growth decelerated to a low basal level and finally growth arrest. The accumulated growth 38 months after stapling was 1.2 mm. Following extraction of staples no further growth was registered during 22 months of observation. At this time the growth plate of the contralateral side had closed (see below).

2. Non-stapled side

The growth rate in the left intact proximal tibia was 13 $\mu\text{m}/\text{day}$ during the initial months following extraction of staples on contralateral side (Fig. 3b). During the subsequent 7 months it decelerated until maturity at SA of 16 years.

Case 2. A boy with an idiopathic progressive leg length discrepancy since early childhood was stapled according to Blount & Clarke (1949) in left proximal tibia at CA 11 years and 3 months (SA approximately 10 years). At this time the right leg was 3.5 cm shorter. Twenty-six months later signs of loosening and extrusion of lateral staples caused re-insertion of medial and lateral staples in proximal tibia. In addition, staples were inserted in the left distal femur. The staples in proximal tibia were extracted 18 months later (Fig. 4). Clinical examination

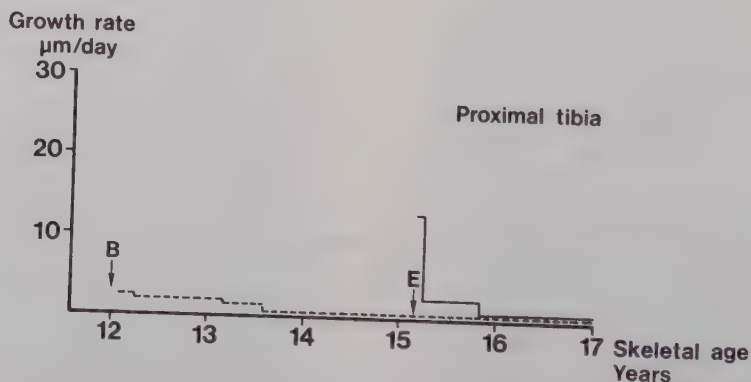


Fig. 3 b. Case 1. Growth diagram. Proximal tibia. Solid lines represent non-stapled left side. Interrupted lines represent stapled right side. B = Blount stapling; E = Extraction of staples.

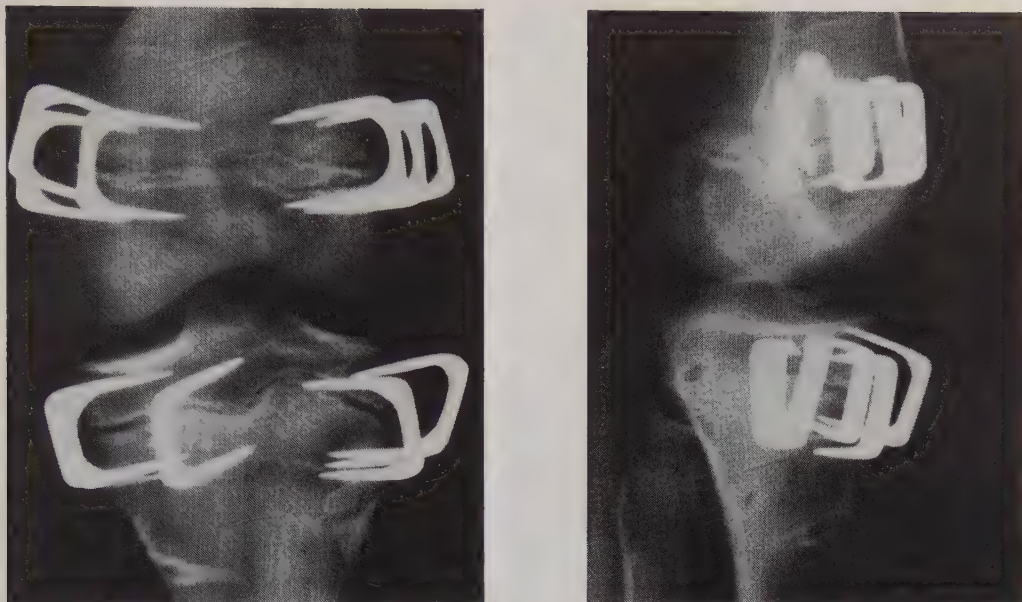


Fig. 4 a and b. Case 2. Standard radiographs of left knee at time of extraction of staples in proximal tibia. a) AP view; b) lateral view.

and orthoradiographic registration 9 months later revealed an overcorrection of 0.5 cm. Standard radiographs (Fig. 5) showed open growth plates in proximal tibia and distal femur bilaterally. The staples in distal femur were then extracted (SA approximately 14 years; CA 15 years 7 months) and he was provided with tantalum balls in proximal tibia and distal femur bilaterally.

A. Longitudinal Growth Rate - Distal Femur

1. Stapled side - stapled growth region

The growth diagram (Fig. 6a) revealed continuous symmetric growth on the medial and lateral side following extraction of staples. During 3 months postoperatively the growth rate was $44 \mu\text{m/day}$; decelerating until maturity at SA approximately 16 years. Termination of growth occurred to simultaneously in the left and right distal femur. The accumulated growth on the left side was 13.6 mm.

2. Non-stapled side

The growth pattern (Fig. 6a) of the right distal femur was normal. The accumulated growth during the period of investigation was 12.5 mm.

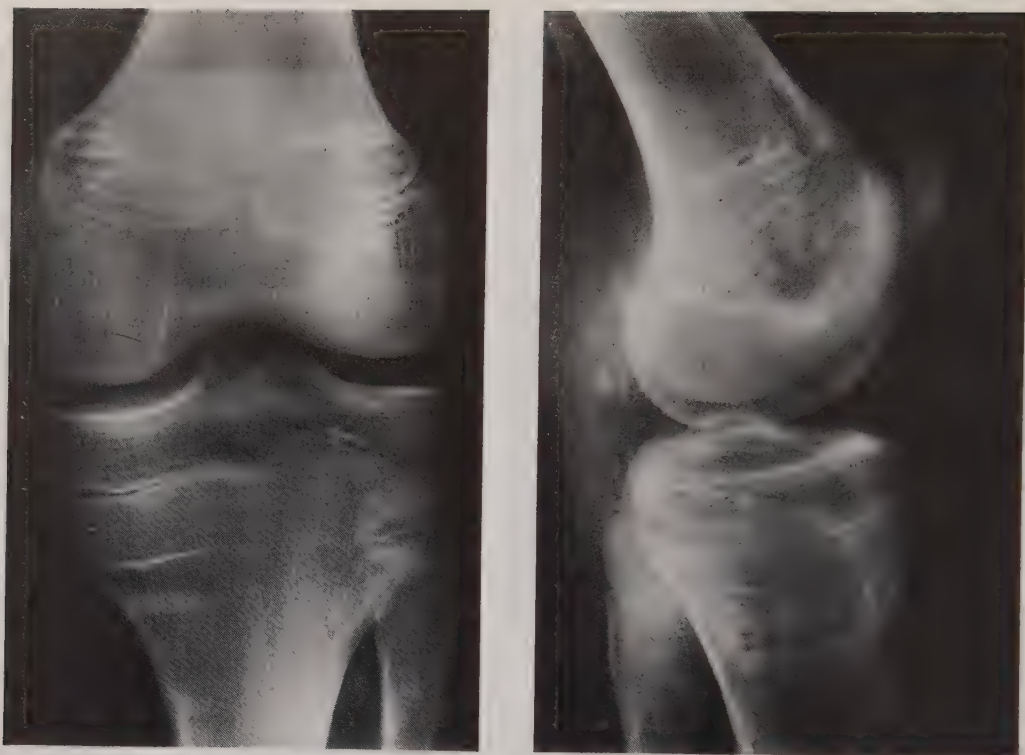


Fig. 5 a and b. Case 2. Standard radiographs of left knee after extraction of staples in distal femur (9 months after extraction of staples in proximal tibia). a) AP view; b) lateral view.

B. Longitudinal Growth Rate - Proximal Tibia

1. Stapled side - stapled growth region

The growth diagram of the left proximal tibia (Fig. 6b) showed growth 9 months after extraction of staples until maturity 30 months later. The growth rate was initially $26 \mu\text{m/day}$ and decelerated to final arrest at SA approximately 16 years and CA 16 years and 8 months. The accumulated growth during the 30 months of investigation was 5.8 mm.

2. Non-stapled side

The growth diagram (Fig. 6b) of the right proximal tibia showed a normal growth pattern. The growth plate closed at SA approximately 15 years. The accumulated growth during the period of investigation was 6.4 mm.

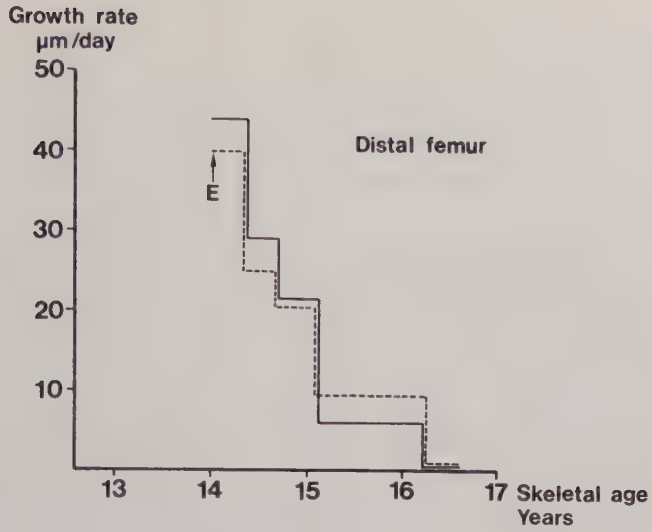


Fig. 6 a. Case 2. Growth diagrams. Distal femur. Solid lines represent non-stapled side. Interrupted lines represent stapled side. E = Extraction of staples.

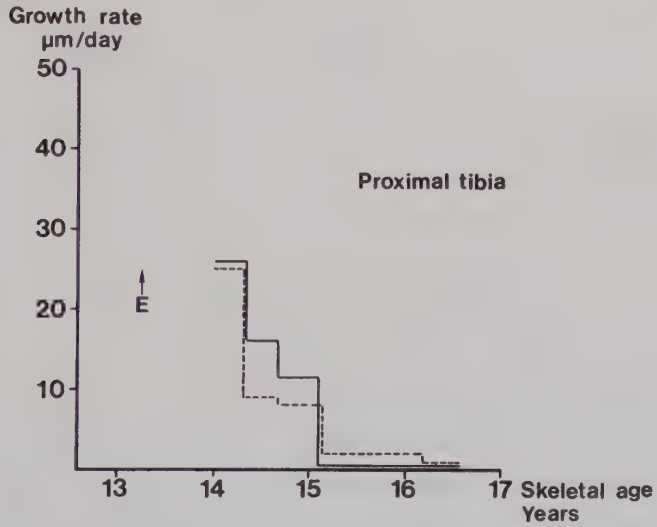


Fig. 6 b. Case 2. Growth diagrams. Proximal tibia. Solid lines represent non-stapled side. Interrupted lines represent stapled side. E = Extraction of staples.

DISCUSSION

The remaining growth potential following a period of temporary growth retardation has been difficult to assess (Blount & Zeier 1952). Standard radiographs including orthoroentgenograms provide only crude measurements of longitudinal growth. Information on the growth potential from roentgenographic changes in the growth region following stapling is lacking (Green & Anderson 1957).

On the basis of roentgenographic findings, Nordentoft (1964) listed criterias to estimate growth and growth arrest after extraction of staples. The most reliable information was obtained from the condensed line at the junction of the growth plate and the metaphysis. Absence of this line indicated that complete physeodesis had not occurred.

Brockway et al. (1954) stated that longitudinal growth continued normally after removal of staples but excluded cases of physeal arrest. McGibbon et al. (1962) concluded that resumption of normal growth was more often obtained after stapling at the age of 9 and extraction at 11 than after stapling at 12 and extraction at the age of 14.

Blount & Zeier (1952) claimed the existence of accelerated growth after removal of staples in some cases. The accelerated growth was compensated for by premature closing of the growth plate (Dalton & Carpenter 1954). The increased growth was explained by a stimulating effect of operative trauma at extraction of staples (Blount & Zeier 1952). Absence of growth, following removal of staples, in spite of radiographically open growth plates, was considered due to local damage at surgery (Brockway et al. 1954, McGibbon et al. 1962).

The present investigation demonstrates the usefulness of RSA for determination of longitudinal growth rates in stapled and non-stapled growth regions, thus facilitating the evaluation of remaining growth potential prior to extraction of staples. Two boys with unilateral leg shortenings were investigated. Case 1 was stapled in the proximal tibia for 3 years; Case 2 in the distal femur and proximal tibia for 2 and $3\frac{1}{2}$ years, respectively. Staples were extracted approximately $\frac{1}{2}$ and 2 years, respectively, prior to termination of growth in the contralateral non-stapled growth region. At this time the stapled growth plates of Case 1 were partially open (Figs 1 and 2) and of Case 2 open (Figs 4 and 5).

In Case 1, growth arrest occurred in the contralateral intact growth region 8 months later, and there was no resumption of growth in the previously stapled proximal tibia (Fig. 3b). These findings are in agreement with those of earlier studies (Blount & Zeier 1952, Green & Anderson 1957, McGibbon et al. 1962, Nordentoft 1964) indicating that resumption of growth cannot be expected if staples are extracted less than 10 months prior to termination of growth in intact growth regions at the knee. In Case 2, the growth diagram showed normal

growth after the extraction of staples in the distal femur, and termination of growth occurred simultaneously with the contralateral intact growth region 27 months later (Fig. 4). Growth decelerated at the same rate as in the contralateral non-stapled side. Studying biopsies from growth plates, Goff (1960) did not find histologic evidence of remaining "osteogenetic power" in the growth plates where staples were left in place for more than 44 months. However, in Case 2, stapled for a total of 44 months, the staples were reinserted after 26 months because of inefficiency. Efficiency of staples must be considered when discussing growth after removal of staples as stated by Nordentoft (1964). The staples in distal femur of Case 2 were extracted after 27 months. The staples were considered efficient as found by clinical and radiographical examinations at follow-up. The growth diagram showed normal growth after extraction of the staples, and the growth decelerated at the same rate as in the contralateral non-stapled side and fused almost at the same time in the same growth region, but later for distal femur compared to the proximal tibia. There were no indication of growth stimulation after removal of staples or earlier closure of the previously stapled growth plate as Blount & Zeier (1952) stated. Furthermore, the origin of the unequal growth must be considered.

In a previous investigation the pattern of growth retardation following stapling was investigated with the roentgen stereophotogrammetric analysis (Bylander et al. 1982). Provided the staples were placed properly, complete growth arrest was achieved in shorter time with increasing skeletal age. Slow deceleration and basal growth level were registered in boys stapled before SA of 14 years and in girls of 12 years. Complete growth arrest was present in girls within 2-10 months when stapled at SA of above 12 years and in boys within 2-6 months when stapled at SA of above 14 years. The ability to resume growth after removal of staples is probably lost shortly before complete growth arrest after stapling. Thus, skeletal age of the patient has to be considered prior to stapling. If early stapling is performed, staples must be extracted after slight overcorrection. To permit stapling at a time which will yield coinciding leg length at maturity, the methods for predicting remaining growth must be improved as the existing techniques are inexact. Probably these difficulties in growth prediction are possible to reduce, using the RSA, since it is possible to determine the growth rates of the actual growth regions, and also to assess the skeletal maturity by comparing the growth rates in different growth regions of the same individual.

In conclusion, the RSA permits growth rate analysis in short time intervals with high accuracy and is suitable to check growth after stapling or to determine growth in intact regions. The ability to resume growth after removal of staples is probably lost shortly before complete growth arrest.

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V

DYNAMICS OF GROWTH RETARDATION AFTER PHEMISTER PHYSEODESIS A Roentgen Stereophotogrammetric Analysis

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ABSTRACT

Phemister physeodesis (epiphyseodesis) was performed in two boys in order to reduce a progressive leg length discrepancy. Growth rate determinations at the region of surgery and in intact growth regions were obtained with high accuracy using the roentgen stereophotogrammetric technique. Presented are standard radiography, histologic appearance of the growth plate at time of surgery and the growth pattern in intact and operated growth regions. Standard radiographs were inaccurate for determination of growth potentials in separate growth regions. Biopsies from the growth regions in distal femur and proximal tibia are shown as histologic evidence of active growth at time of surgery. The growth diagrams showed complete and irreversible growth arrest after Phemister physeodesis. However, growth retardation occurred more rapid after Phemister physeodesis than after Blount stapling and complete growth arrest was registered within months.

INTRODUCTION

Phemister in 1933 presented a method for permanent growth arrest in order to reduce progressive angular or longitudinal deformity in the growing child. The Phemister physeodesis (epiphyseodesis) is a final and irreversible procedure (Green & Anderson 1957, Karaharju & Raunio 1970). The cartilage plate between the bony epiphysis and metaphysis is destroyed at surgery and plugs of cancellous bone reinserted for a solid bony fusion to be achieved. The original technique has been modified in several investigations (White & Stubbins 1944, Regan & Chatterton 1946, Van Nes 1957, Goff 1960, Nordentoft 1964, Tachdjian 1972). The modifications have improved the prediction reliability and the final outcome of surgery.

Accurate estimation of growth pre- and post-operatively is important to determine the proper time of surgery and will determine the end result provided careful and accurate operative

technique has been performed. Because of the irreversibility in the Phemister procedure, overcorrection must be avoided. Complications of the procedure include over- and undercorrection, fractures (physeolysis), asymmetric growth and infections (White & Stubbins 1944, Straub et al. 1945, Green & Anderson 1957, Högberg & Lindström 1957, Goff 1960, Nordentoft 1964, Morscher & Taillard 1965, Menelaus 1966, Højstrup & Pilgaard 1969). Over- and undercorrection can be avoided by careful and accurate pre-operative planning and growth rate determination. Estimation of skeletal age is essential (Green & Anderson 1947, 1957, Karaharju & Raunio 1970, Blair et al. 1982).

Accurate and sensitive methods to analyze longitudinal growth rate at separate growth regions have not been available in clinical practice. The roentgen stereophotogrammetric analysis (RSA) permits longitudinal growth rate analysis with high accuracy (Selvik 1974, Aronson 1976). In the present study RSA was applied in growth regions subjected to Phemister physeodesis in order to facilitate the pre-operative planning and/or to check the efficiency of surgery and to elucidate the pattern of growth retardation.

METHODS

The pre-operative planning include estimation of remaining growth potential which was calculated according to Green & Anderson (1947). Skeletal age (SA) at time of surgery was assessed from radiographs of the hand and wrist according to Greulich & Pyle (1950).

A modified physeodesis according to Phemister (Tachdjian 1972) was performed in distal femur (Case 1) and in right distal femur and proximal tibia (Case 2).

Biopsies were cut out medially from the growth regions subjected to surgery. The specimens were fixed in Bouin's solution and decalcified in equal parts of 7% sodium formate and 40%

formic acid for three weeks. Paraffin sections about 10 μm thick were prepared with help of a slide microtome. The paraffin sections were stretched on water (Clayden 1962) at a temperature of at most 37⁰ and then allowed to dry in the air at room temperature. The sections were stained in haematoxylin-eosin according to Ehrlich and were mounted in DePeX (Gurr, London). Among the samples selected characteristic areas were chosen and exemplified (Figs. 3 and 6).

The patients were mobilized post-operatively without plaster and with full weight-bearing after two weeks. The post-operative follow-up included clinical examination and measurement of leg length with tape, orthodiagraphic radiographs, standard radiographs of operated knee and examinations with the RSA at intervals ranging from four to twelve weeks.

Roentgen stereophotogrammetric analysis (RSA)

The roentgen stereophotogrammetric technique (Selvik 1974) was utilized for longitudinal growth rate determinations. Spherical tantalum balls, 0.5 mm in diameter, were implanted percutaneously and through the operative incision into the metaphysis and bony epiphysis of the distal femur and proximal tibia bilaterally (Aronson 1976). The patients were examined at varying intervals until skeletal maturity. The calibration cage Model 2 according to Selvik was used and the position of the cage markers in the bone on the roentgen films were determined in a precision instrument for aerial photogrammetry (Wild Autograph A8). The three-dimensional coordinates and the distance changes for the bone markers were calculated in a computer (Univac 1100/80) and longitudinal growth rate was thus determined. The error of the method is 30-50 μm for each examination, corresponding to approximately 1-2 $\mu\text{m}/\text{day}$ at monthly registration intervals (Selvik 1974, Aronson 1976, Bylander et al. 1981b).

CASE REPORTS AND RESULTS

Case 1. This boy was hit by a car at chronological age (CA) twelve years and five months. He sustained a physal fracture of the right distal femur, with the bony epiphysis rotated anteriorly (Bylander et al. 1981a). It was classified as Type I according to Salter & Harris (1963). A closed reduction was performed and a plaster of Paris was applied for five weeks. The knee motion was examined in general anesthesia four weeks after removal of the cast, and tantalum balls implanted. Clinical and roentgenological examination 15 months after injury revealed the injured right leg 22 mm shorter than the left leg. Standard radiographs of the right knee (Fig. 1b) revealed obliteration of the growth plate in distal femur. Standard radiographs of the left intact knee showed open growth plates in distal femur and proximal tibia (Fig. 1a). SA was approximately $13\frac{1}{2}$ years. To prevent further progressive leg length discrepancy, he was operated with a Phemister physeodesis in left distal femur and with Blount stapling (Blount & Clarke 1949) in the left proximal tibia.

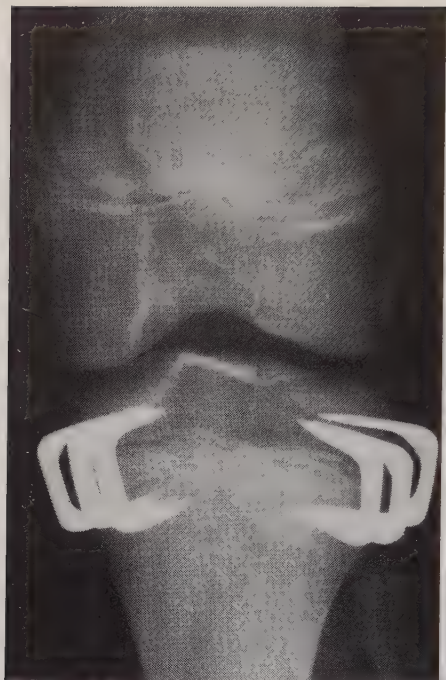
A. Growth analysis

Growth rate measurements were performed at nine weeks after fracture (initial rate) and on three more occasions until the Phemister physeodesis twelve months later.

The initial rates in distal femur and proximal tibia of the left side were 44 and 20 $\mu\text{m}/\text{day}$, respectively; the subsequent rates 50 and 30 $\mu\text{m}/\text{day}$; the accumulated growth over the twelve months 17.8 and 10.8 mm, respectively (Fig. 2a).

On the injury side, the initial rates in distal femur and proximal tibia were 1 and 17 $\mu\text{m}/\text{day}$, respectively; the subsequent rates 1 and 35 (38, 36, 30) $\mu\text{m}/\text{day}$; the accumulated growth over the twelve months 0.1 and 9.3 mm; respectively (Fig. 2b).

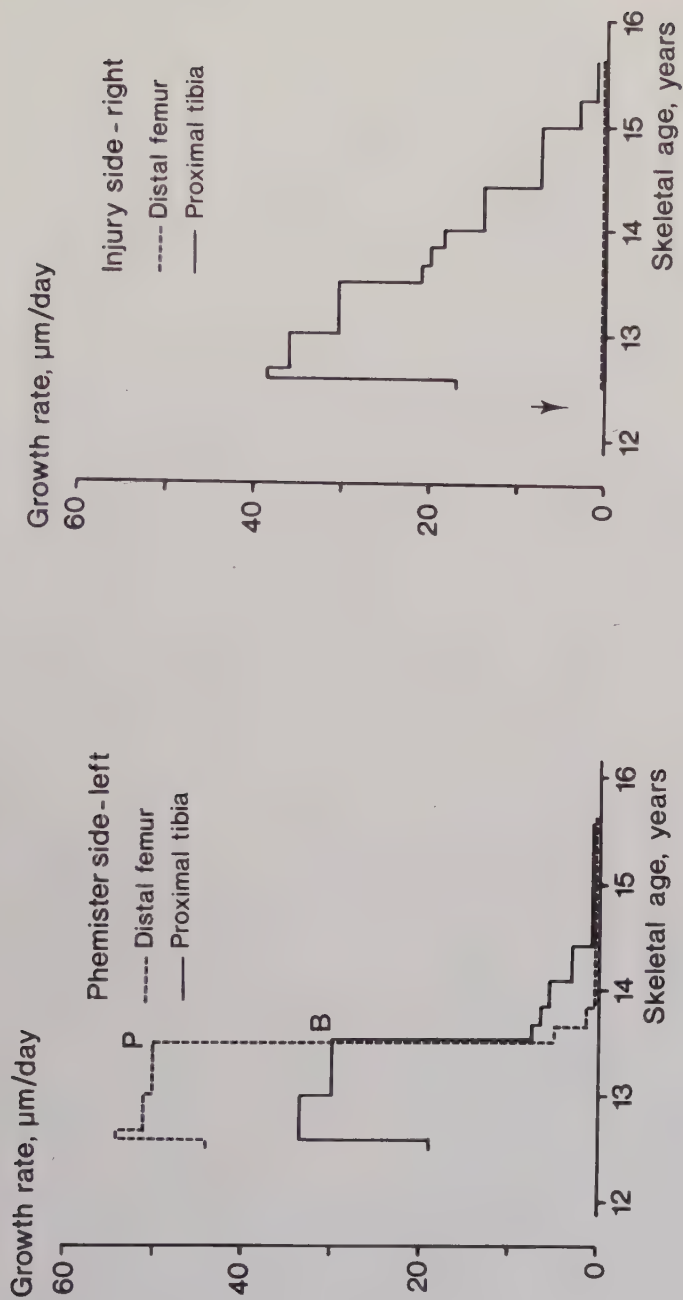
Following Phemister and Blount physeodesis in distal femur and proximal tibia, respectively, seven growth rate measurements were performed until skeletal maturity. The results are presented in growth diagrams in Figs. 2a and b and in Table I.



Figs. 1a and b

Case 1. Radiographs of left and right knee (AP views) 15 months after injury at time of Phemister and Blount physeodesis.

a) Phemister side - left knee. b) Injury side - right knee.



Figs. 2a and b
 Case 1. Growth diagrams of distal femur and proximal tibia.
 P = Phemister physeodesis, B = Blount stapling.
 a) Phemister side - left knee. b) Injury side - right knee.

TABLE I. Longitudinal growth analysis after physodesis

Growth analysis									
Surgery*		Initial period (µm/day) 0-2 months		Subsequent period (µm/day) 2-12 (15) months		Accumulated growth (mm)		Figure	
Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
<u>A. Phemister side</u>									
1. Distal femur	P	P	5	3	4 → 0	0.7	0.2	3a	5a
2. Proximal tibia	B	P	7	4	6 → 0	1.1	0.5	3a	5a
3. Distal tibia & fibula	-	I	-	8	-	-	1.4	-	5b
<u>A. Injury side</u>									
1. Distal femur	I	I	1	2	1	0.1	0.1	3b	5a
2. Proximal tibia	I	I	17	1	38 → 0	9.3	0.1	3b	5a
3. Distal tibia & fibula	-	I	-	0	-	-	0	-	5b

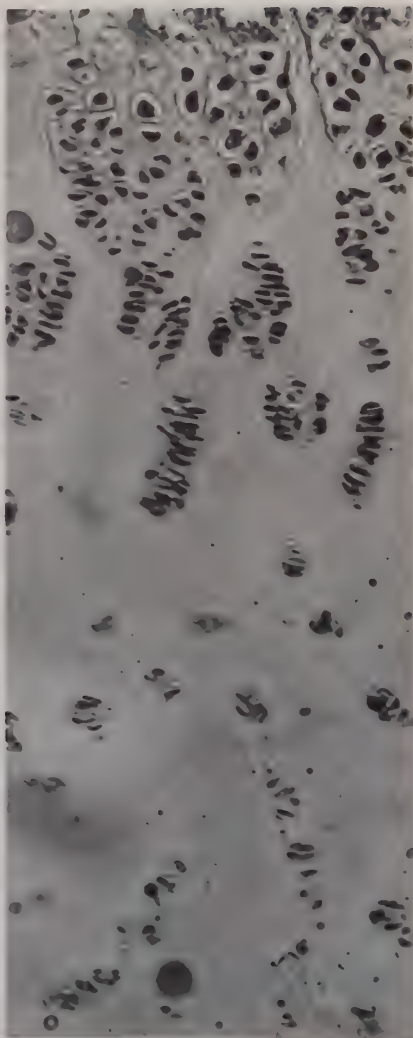
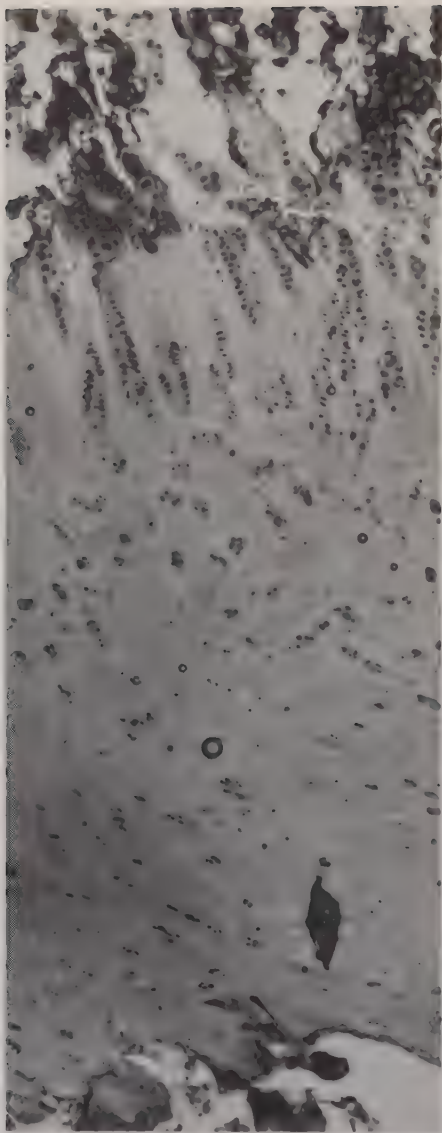
* P = Phemister physodesis, B = Blount stapling, I = Traumatic physodesis, I = Intact

B. Microscopic analysis and radiographs

The biopsy from the growth region in the distal femur at the time of the Phemister procedure, showed the cellular arrangement of an active growth plate (Fig. 3a and b). The undifferentiated cartilage and the regular architecture of the columnar zone, including the proliferative cells and the hypertrophic cells with degenerative nuclei, are clearly visible. The height of the undifferentiated zone was approximately 1200 μm and of the columnar zone 500 μm ; in total approximately 1700 μm .

The standard radiographs of the left knee (Phemister side) showed open growth plates in the distal femur and the proximal tibia at the time of the Phemister and Blount procedures (Fig. 1a). A condensation line (line of growth arrest) was demonstrated in the distal femur, representing the physeal injury in the contralateral distal femur 15 months earlier. The distance between the condensation line and the growth plate was approximately 20 mm (17-23 mm) corresponding to the accumulated growth of 17.8 mm measured with the RSA over a slightly shorter period. Condensation lines could not be identified in proximal tibia bilaterally.

Case 2. This boy sustained a traumatic diaphyseal fracture of his right femur at CA 14 years and nine months. The injury was treated with tibial pin-traction for six weeks and healed with approximately 20 mm overlapping of distal and proximal fragments and with a slight varus angulation. Orthodiagraphic radiographs and clinical examination eight months later, revealed a leg length discrepancy of 37 mm with the injured right leg shorter than the left leg. Standard radiographs of the right and left knees showed open growth plates in distal femur and proximal tibia bilaterally (Figs. 4a and b). SA was assessed to 14 years. A Phemister physeodesis was performed in the left distal femur and proximal tibia in order to reduce the leg length discrepancy. Tantalum balls were implanted in distal femur, in distal and proximal tibia and distal fibula bilaterally at surgery.



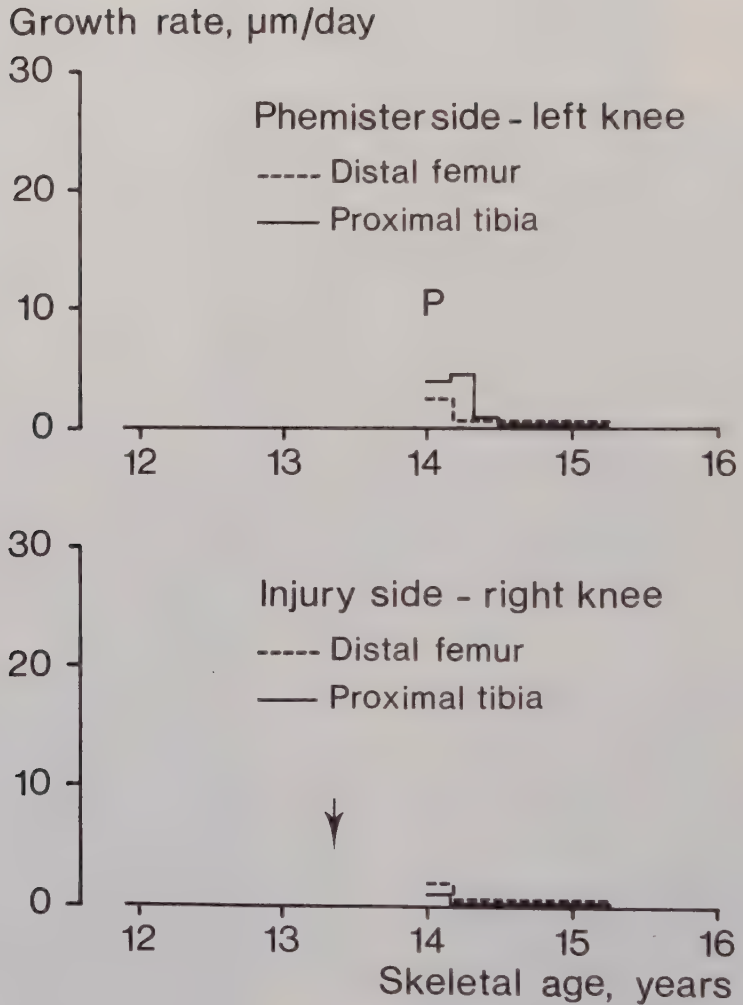
Figs 3a and b

Case 1. Microscopic analysis of the growth plate in left distal femur (metaphysis above and the bony epiphysis below).

a) Magnification **60X** b) Magnification **140 X**



Figs. 4a and b
Case 2. Radiographs of left and right knee (AP views) eight months after injury at time of Pnemister physeodesis.
a) Pnemister side - left knee. b) Injury side - right knee.

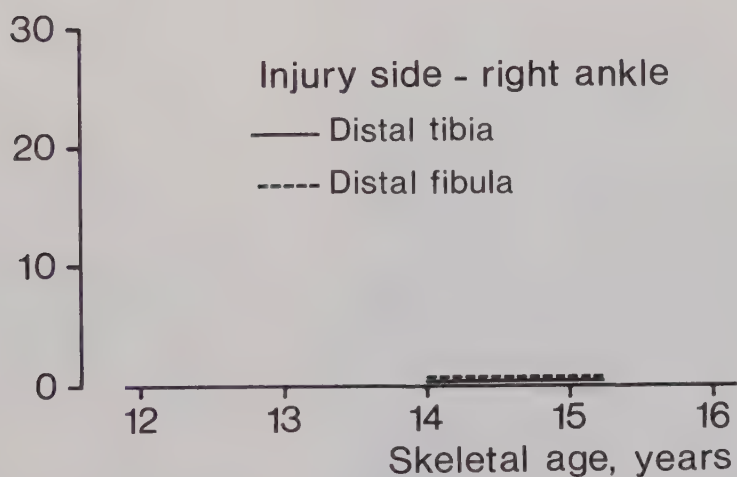
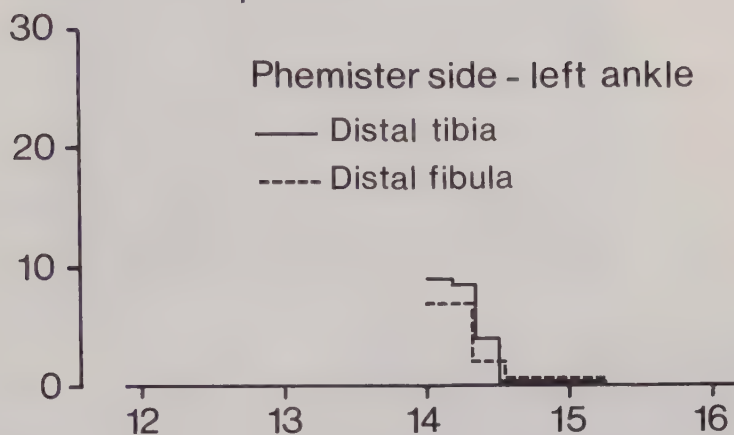


Figs. 5a and b

Case 2. Growth diagrams of distal femur, proximal tibia, distal tibia and distal fibula. P = Phemister physeodesis. Arrow indicates time of injury.

a) Knee regions - left and right side. b) Ankle regions - left and right side.

Growth rate, $\mu\text{m}/\text{day}$



A. Growth analysis

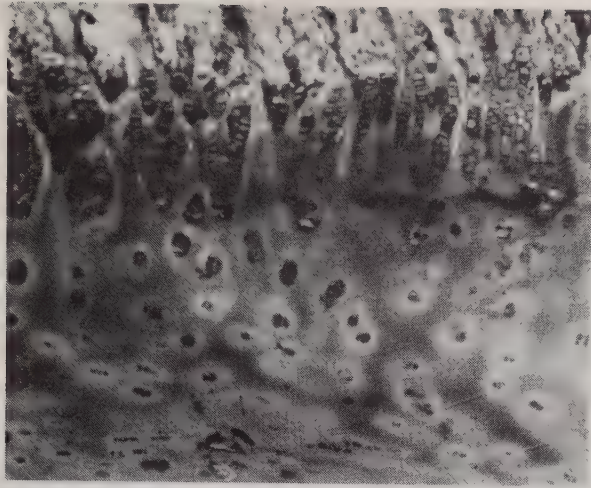
Following the Phemister physeodesis in distal femur and proximal tibia, five growth rate measurements were performed. In addition, the growth rate was registered in distal tibia and fibula bilaterally.

The growth rates in distal femur, proximal tibia, distal tibia and distal fibula were close to zero in the short injured right leg. In the left leg (Phemister side) the growth rates after surgery in distal femur and proximal tibia were decreasing to growth arrest in short time. The growth rates in distal tibia and fibula showed decreasing growth rates from a slightly higher level to growth arrest at skeletal maturity. The results are presented in growth diagrams in Figs. 5a and b and in Table I.

B. Microscopic analysis and radiographs

The biopsies from the left distal femur and proximal tibia (Phemister side) at the time of the Phemister operation showed the cellular arrangement of an active plate (Figs. 6a and b). The undifferentiated cartilage and the columnar zone are demonstrated. The proliferative and hypertrophic cells are uniformly arranged in regular cellular columns. The height of the undifferentiated and columnar zones were 700 μm and 400 μm , respectively; in total approximately 1100 μm . The biopsy from the proximal tibial growth region showed similar cellular arrangements and a regular arrangement of the undifferentiated and differentiated cartilage zones. The height of the undifferentiated and columnar zones were 500 and 400 μm , respectively; in total approximately 900 μm .

The standard radiographs showed bilaterally open growth plates in distal femur and proximal tibia (Figs. 4a and b). The condensation lines (lines of growth arrest) in the left distal femur and the left proximal tibia represented the diaphyseal femoral injury in the contralateral side (injury side) eight months prior to the Phemister procedures. The distances between the condensation line and the growth plate were technically difficult to measure (approximately 8-10 mm and 3-5 mm in distal femur and



Figs. 6a and b
Case 2. Microscopic analysis of the growth plate in the left distal femur (metaphysis above and the bony epiphysis below).

a) Magnification **60 X**

b) Magnification **150 X**

proximal tibia, respectively). This corresponds to a mean growth rate during the eight months of 30-40 and 15-20 $\mu\text{m}/\text{day}$ in the distal femur and proximal tibia, respectively.

DISCUSSION

Growth after the Phemister procedure (Phemister 1933) has been registered in clinical investigations and experimentally (Johnson & Southwick 1960) and presumed to occur within the first year, if at all (Straub et al. 1945, Green & Anderson 1957, Nordentoft 1964, Goff 1960, Morscher & Taillard 1965). Partial fusion or non-fusion, resulting in asymmetric growth and continued growth, respectively, have been reported (Straub et al. 1945, Green & Anderson 1957, Nordentoft 1964, Morscher & Taillard 1965), and experimental investigations have proposed the possible development of a bony bridge (Johnson and Southwick 1960).

Growth appearing after the first post-operative year has been ascribed to inadequate operative technique (Green & Anderson 1957), and numerous modifications of the original technique, have been presented (White & Stubbins 1944, Regan & Chatterton 1946, Van Nes 1957, Goff 1960, Nordentoft 1964, Tachdjian 1972).

In clinical practice it has not been possible to assess the remaining growth potential with satisfactory accuracy. Lines of growth arrest (Harris 1931) have been used but measurements are not sufficiently accurate. The RSA permits longitudinal growth rate analysis with high accuracy (Selvik 1974, Aronson 1976, Bylander et al. 1981a and b, 1982, Kärrholm et al. 1982).

The longitudinal growth rates in distal femur and proximal tibia bilaterally were registered pre- and post-operatively in Case 1. Pre-operative standard radiographs and microscopic analysis showed that the growth region in the distal femur was open and active. With RSA the growth rate in distal femur (Phemister side) was 50 $\mu\text{m}/\text{day}$ pre-operatively and decreased abruptly to

5 $\mu\text{m}/\text{day}$ following surgery. Complete growth arrest occurred within six months. The growth rate decreased similarly from 30 to 7 $\mu\text{m}/\text{day}$ in proximal tibia after the stapling procedure. However, the pattern of growth retardation following the stapling procedure (Bylander et al. 1982) in proximal tibia (growth arrest within twelve months) was different from the retardation growth pattern after the Phemister physeodesis in distal femur (growth arrest within six months).

The growth pattern registered in Case 2 merits further comments. The history and the development of the leg length discrepancy, indicate that an anisomelia was present prior to the traumatic diaphyseal femoral fracture. The fracture was treated with tibial pin-traction including a shortening of a few centimetres. This treatment has probably enhanced a pre-existing linear discrepancy of unknown etiology. One would expect that hyperemia, caused by the diaphyseal fracture and the treatment with pin-traction, would result in a temporary growth stimulation (Hansson 1967, Hedström 1969). However, the pre-existing compromised growth potential of the leg resulted in a premature termination of growth in the regions of the knee and ankle. Thus, the growth diagrams of the short leg (injury side) showed termination of growth in the distal tibia and fibula, at least six months prior to termination of growth in the intact growth regions of the long leg (Phemister side). From post-operative RSA-values in distal tibia and fibula (Phemister side), the pre-operative growth rates in the proximal tibia and distal femur on the same side can be estimated to approximately 15 and 30 $\mu\text{m}/\text{day}$, respectively (Bylander et al. 1982). These values compare favourable with the rough estimates obtained from standard radiographs and microscopic analysis of biopsies taken at surgery.

The growth rates following the Phemister procedure decreased rapidly and growth arrest occurred within six months of surgery.

Kember & Sissons (1976) have shown that the general appearance of the histological arrangement in the growth plate of distal femur in children, does not change until growth rate

deceleration towards fusion of the growth plate begins. In their investigation the height of the columnar zone in two boys 13 and 14 years (CA) old was approximately 500 μm . The microscopic analysis in the present investigation showed corresponding values. The height of the columnar zones in Cases 1 and 2 were 500 and 400 μm , respectively, corresponding to a growth rate of 50 and 30 $\mu\text{m}/\text{day}$, respectively, as registered by the roentgen stereophotogrammetric technique and corresponds well to the values presented by Kember & Sissons (1976).

In conclusion:

1. Standard radiographs were found inaccurate for determining growth potential in separate growth regions.
2. Biopsies from regions subjected to Phemister physeodesis will provide rough estimates of growth potential at the time of surgery.
3. Unless information on the remaining growth potential in both legs is available the final leg length discrepancy can not be accurately predicted.
4. Growth rate decreases rapidly to complete growth arrest within months after Phemister physeodesis.
5. The RSA was found suitable for pre- and post-operative growth rate determinations thus facilitating prediction and the early detection of complications, such as incomplete growth arrest or asymmetric growth following the Phemister physeodesis.

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VI

CORRECTION BY STAPLING OF PROGRESSIVE ANGULAR DEFORMITY AFTER PHYSEAL INJURY OF PROXIMAL TIBIA

A Roentgen Stereophotogrammetric Analysis

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ABSTRACT

A traumatic physeal injury, classified as Salter-Harris Type IV, in the left proximal tibia of an eight-year-old boy resulted in a progressive valgus deformity. A condensed area in the lateral part of the growth region developed radiographically and medial stapling was performed. Three-dimensional determinations of growth dynamics were performed using the roentgen stereophotogrammetric technique (RSA).

The growth rate decreased laterally after the injury but with no signs of complete growth arrest, indicating the formation of an osseo-fibrous connection between the bony epiphysis and metaphysis. The growth rate increased laterally after the procedure and decreased medially. The valgus deformity was thus reduced and the staples were removed at overcorrection. Normal symmetrical growth was registered after the initial post-operative month following extraction of the staples.

Conclusions: The roentgen stereophotogrammetric technique permits analysis of longitudinal growth and rotational movements during short periods with high accuracy, making prediction possible and facilitating the checking of growth after surgical procedures. The formation of an osseo-fibrous connection could be demonstrated. Insertion of staples medially resulted in increased growth corresponding to the defect laterally and in reorganisation of the growth plate. Extraction of the staples after overcorrection resulted in a temporary increase of the growth rate medially, probably as a result of the elimination of the compression forces medially from the staples. Unilateral stapling is an alternative besides the Langenskiöld operation for the correction of angular deformity.

INTRODUCTION

Growth disturbance after physeal injury is difficult to predict. Several attempts have been made to classify physeal fractures especially involving growth regions of the knee in order to predict future growth disturbances (1,2,4,14,29,31,33). The classifications are similar and the prognostic validity is based on the results of experimental investigations. The prognostic value of the classification system of Salter and Harris has been questioned (9,25,28).

The development of an angular deformity after physeal injury in the knee region is a serious problem. Surgical procedures as stapling according to Blount, the Langenskiöld operation and distraction physeolysis as well as osteotomies and conservative techniques have been proposed (5,23,24,26,30,38). Spontaneous correction occurs but is not common (9,12). Experimental and clinical studies have proposed the formation of a bridge of bone across the growth plate, resulting in asymmetric growth and progressive angular deformity (19,24). The identification of a condensed area or a defect in the growth region by standard radiographs and tomography has been interpreted as a bony connection between the metaphysis and bony epiphysis (11,12,13,24,30). Previous clinical and experimental studies have been contradictory regarding continuous growth capacity after the microscopic and radiographic evidence of obliteration across the growth region (10,19,27).

The present investigation is a case report of a boy with a Salter and Harris Type IV injury in his left lateral proximal tibia. A progressive valgus deformity developed and he was treated with staples medially. Markers of 0.5 mm tantalum balls were implanted bilaterally in the metaphysis and bony epiphysis in the proximal tibia and distal femur five weeks after the injury, thus permitting a roentgen stereophotogrammetric analysis (RSA) with high accuracy of the growth dynamics (32).

METHOD

The roentgen stereophotogrammetric analysis (RSA) according to Selvik (32) was used for longitudinal growth rate and kinematic calculations. After the three dimensional co-ordinates of tantalum balls, implanted bilaterally in distal femur and proximal tibia, had been determined. The 0.5 mm spherical tantalum balls were implanted percutaneously (3) in general anesthesia five weeks after the physeal injury. At the stapling procedure additional tantalum balls were implanted laterally in the injured left proximal tibia and in addition single markers in distal femur were implanted bilaterally. The growth registrations were performed at varying intervals ranging from four to twelve weeks with the knee placed in a calibration cage Model 2 (32). The changes in distance and the rate of change between the markers in the bony epiphysis and metaphysis were calculated and plotted with computer graphics. The calculations were performed on a Univac 1100/80. Error of the method for longitudinal growth rate is approximately 30 μm , corresponding to 1 to 2 $\mu\text{m}/\text{day}$ at monthly registration intervals (3). A kinematic analysis, using the rigid body model concept, was performed of the left proximal tibia and the segmental rotations about the sagittal (Z), transverse (X) and longitudinal (Y) axes are presented. The error of the kinematic calculations is approximately 0.2° (7,32).

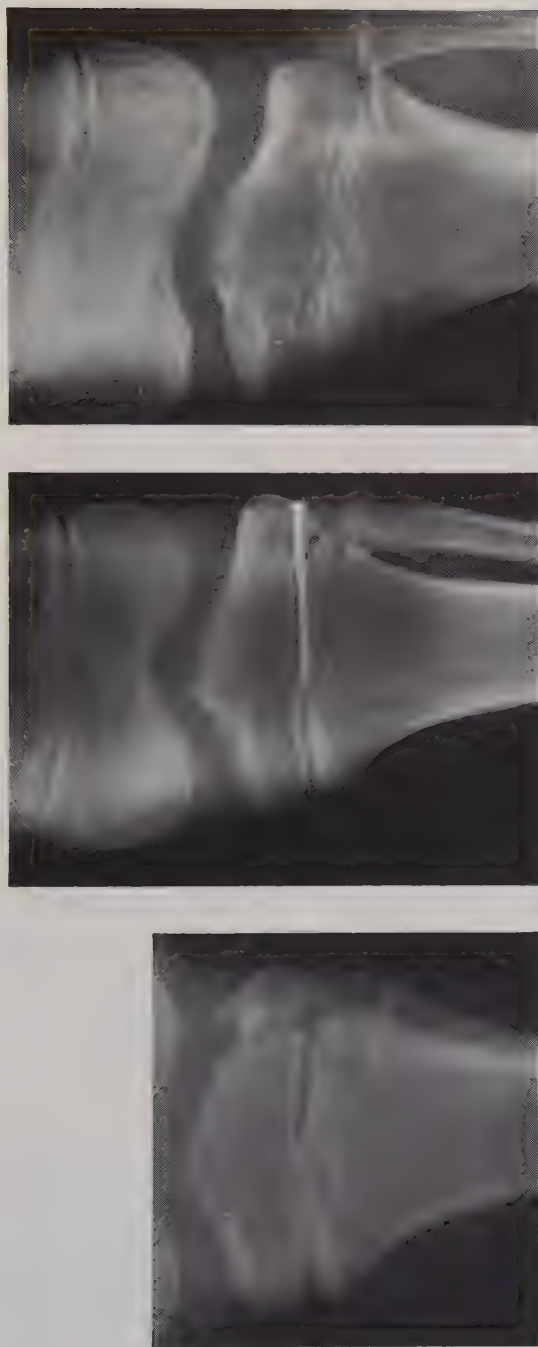
CASE REPORT AND RESULTS

Injury

The boy was run over by a tractor at the age of eight years and eight months. The clinical examination revealed severe instability of the left knee. The radiographs (Fig. 1a) showed a displaced comminute fracture through the lateral part of the left proximal tibial growth plate, classified according to Salter and Harris as Type IV, and a fracture of the left proximal fibular metaphysis.

Fracture treatment

The fracture system through the bony epiphysis, the growth region



Figs. 1 a-c
Standard radiographs of the left knee. AP views.
a) After the injury. b) After the open reduction and fixation.
c) Twelve months after the injury. (Note the lateral defect in the growth plate; the position of the tantalum balls and the valgus deformity indicating asymmetric growth.)

and the metaphysis was reduced and fixed with a pin (Fig. 1b). The knee was placed in a plaster of Paris for three weeks; after a further two weeks without plaster and no weight-bearing, the pin was extracted and the tantalum balls were implanted in general anesthesia and under fluoroscopic control.

Development of deformity

During 19 months, from the time of injury to the time for a corrective operation (age eight years and eight months to ten years and three months) the boy developed a valgus deformity, eventually obvious on clinical examination (20°) and on standard radiographs (Fig. 1c).

The progressive valgus deformity was evident with the RSA already three months after the injury. At this time there was an obvious discrepancy in growth rates medially and laterally. The kinematic analysis showed increasing valgus and antecurvation deformity evident six months after the injury (Fig. 2). The standard radiographs (Fig. 1c) including tomography twelve months after the injury showed a condensed area in the lateral part of the left proximal tibial growth plate indicating a bony bridge or an osseo-fibrous connection between the bony epiphysis and metaphysis.

After 19 months the kinematic analysis showed pronounced and progressively worsening valgus deformity; pronounced antecurvation and increasing outward torsion. Simultaneously, growth rates medially and laterally showed a continuous decrease; lateral growth being pronouncedly less than the medial growth (Fig. 3 a and b). At this point it was decided that corrective measures were needed.

Treatment of deformity

As corrective operative procedure, the insertion of staples medially was preferred, since the RSA showed growth laterally. Two small straight staples were inserted under fluoroscopic control (Fig. 4a and b). There were no complications and the boy was immediately mobilized without plaster and with full weight-

bearing. The standard radiographs showed the staples in good position (Fig. 4a and b). Additional tantalum balls were implanted laterally in the left proximal tibia and in the distal femur bilaterally at the same time.

Correction of deformity

The staples were left in situ during 30 months (age ten years and three months to twelve years and nine months). Kinematic analysis shortly after the medial stapling procedure showed that the progression of the valgus deformity and antecurvation were immediately interrupted and reversed. Standard radiographs twelve months after medial stapling showed the condensed area displaced in metaphyseal direction and a remaining irregularity in the injured part of the growth region (Fig. 5a and b). After 21 months there was neither valgus deformity nor antecurvation (Fig. 2).

Between 21 months and 30 months after medial stapling, as a sign of overcorrection, a varus deformity developed. Over the same period of time, from corrective medial stapling to extraction of staples, the growth rates laterally and medially increased, the former pronouncedly more than the latter (Fig. 3a). After 21 months the lateral growth rate stabilized at approximately 25 $\mu\text{m}/\text{day}$. Standard radiographs 28 months after medial stapling showed widening of the staples and the condensed area further displaced in metaphyseal direction (Fig. 6a and b).

Development after extraction of staples

The staples were extracted 30 months after the stapling procedure. Immediately after extraction the progressive varus (overcorrection) deformity was interrupted. Already one month later, the medial and lateral growth rates both stabilized at 20 $\mu\text{m}/\text{day}$. Standard radiographs six months after extraction of the staples showed increased irregularity in the growth plate and disappearance of the condensed area within the metaphysis (Fig. 7a and b). The growth rate at this time in the right contralateral intact proximal tibia was 35 $\mu\text{m}/\text{day}$ (Fig. 3b).

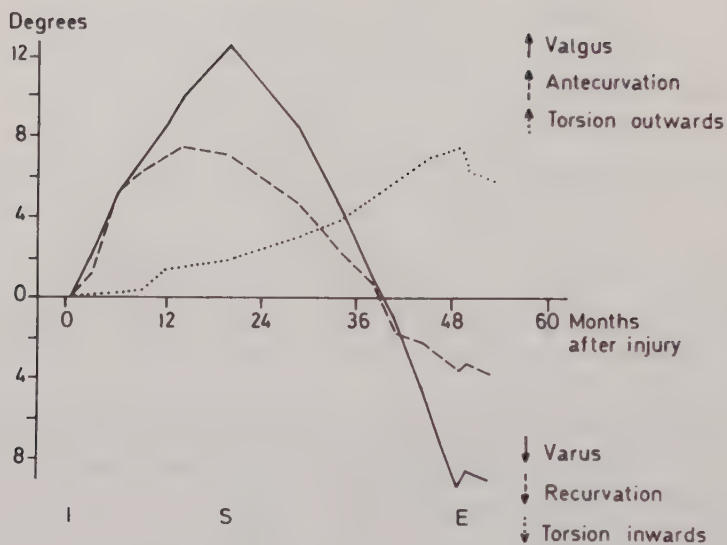
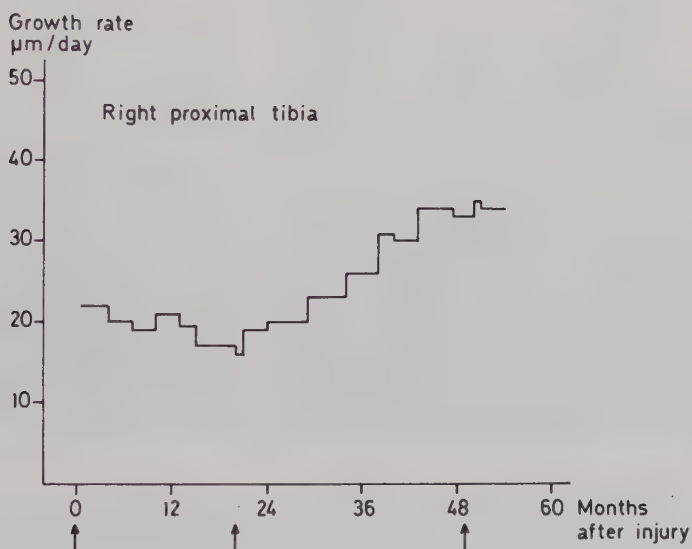
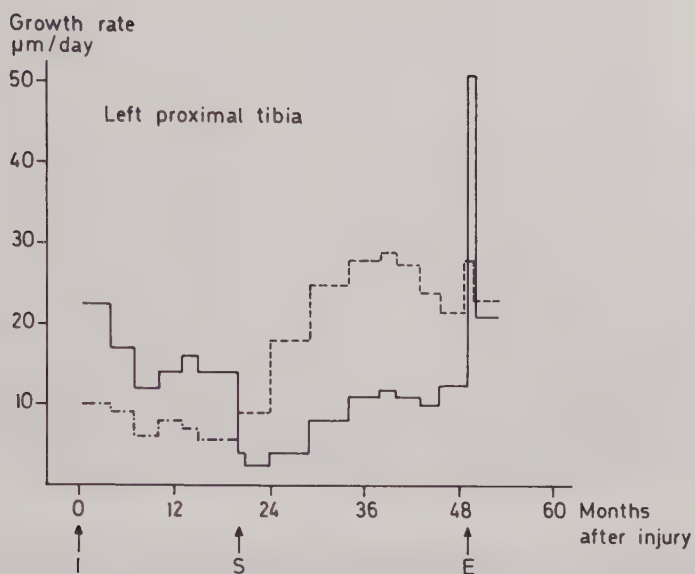


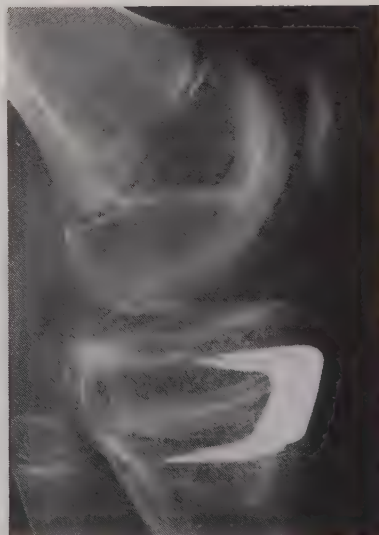
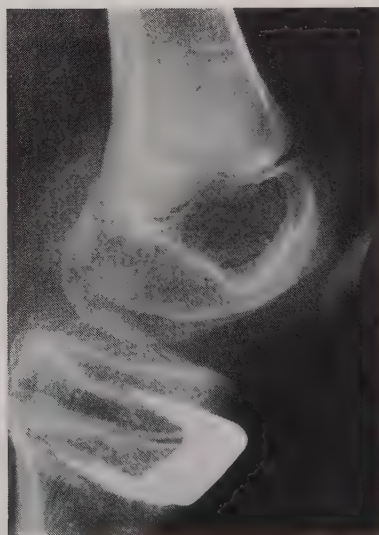
Fig. 2
Kinematic analysis of the left proximal tibia. Rotations of the metaphysis in relation to the bony epiphysis about the three main axes. For abbreviations see Fig. 3.



Figs. 3a and b

Growth diagrams. Longitudinal growth rate. I= injury, S= stapling medially, E= extraction of staples.

a) The left proximal tibia (injured side). (---)= lateral side before stapling; (-.-.-)= lateral side after stapling; (—)= medial side. b) The right proximal tibia (intact side).



Figs. 4a and b

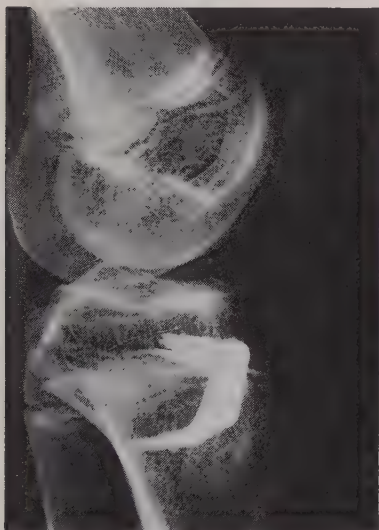
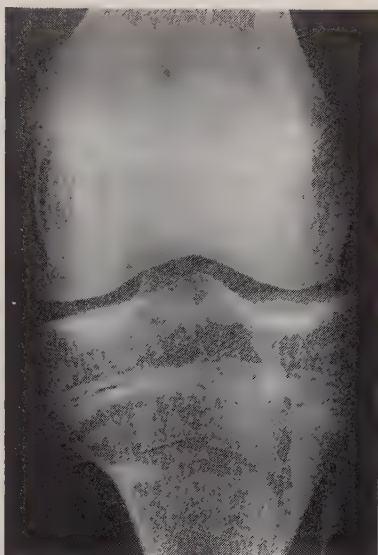
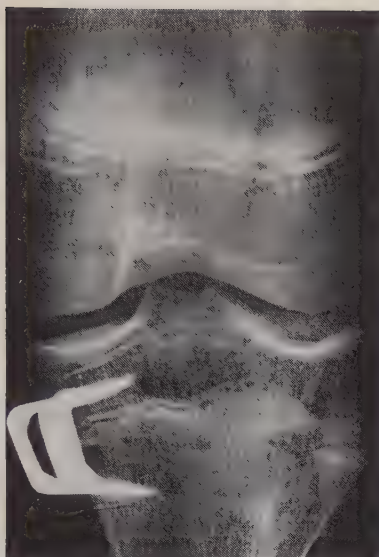
Standard radiographs of the left knee after medial stapling, 19 months after the injury. (Note the condensed area in the lateral part of the growth region and the additional lateral tantalum balls.)

a) AP view. b) Lateral view.

Figs. 5a and b

Standard radiographs of the left knee twelve months after medial stapling. (Note the position of the condensed area, displaced in metaphyseal direction and a remaining irregularity in the injured part of the growth region.)

a) AP view. b) Lateral view.



Figs. 6a and b

Standard radiographs of the left knee 28 months after medial stapling at time of the extraction of staples. (Note the widening of the staples and the position of the condensed area further displaced in metaphyseal direction.)

a) AP view. b) Lateral view.

Figs. 7a and b

Standard radiographs of the left knee six months after extraction of staples. (Note the disappearance of the condensed area within the metaphysis and the increased irregularity in the growth plate and adjacent areas within the epiphysis and the metaphysis.)

a) AP view. b) Lateral view.

Note the condensation line in the bony epiphysis of the left distal femur, indicating the time of injury, which is an expression of the hemispherical growth of the epiphysis (Figs. 1c and 4-7).

DISCUSSION

The radiographic sign of a bony defect or an osseo-fibrous connection in the growth region after a physeal injury indicates growth disturbance. The clinical and radiographical development might reveal impaired growth capacity, indicating increased shortening or angular deformity. However, from clinical and radiographical measurements it is difficult to predict future development (9).

The roentgen stereophotogrammetric analysis (RSA) permits determination of longitudinal growth and rotational movements over short periods with high accuracy (3,7,32). The RSA was used in a boy to evaluate the growth pattern after a physeal Salter-Harris Type IV injury, and to demonstrate the efficiency of a corrective procedure with staples.

Growth disturbance, often with radiographical signs of a bony bridge, is a regular finding after Type IV injuries (6,21,25,31). In this case the radiographs showed an area of condensed bone, usually interpreted as a bony bridge. However, growth was registered during the complete period of investigation indicating that the defect was of osseo-fibrous origin rather than a solid connection between the bony epiphysis and metaphysis. If the latter had been the case, growth would have been completely arrested. Furthermore, after the stapling procedure, the area of condensed bone appeared to gradually shift in metaphyseal direction. This was a result of the elongation of the metaphysis in proximal direction with growth, and a probable regeneration of the growth plate in the earlier defect. This was documented by the radiographical finding of an almost intact plate and a constant relationship between the area of condensed bone and the fixed tantalum balls in the bone. Since the medial stapling procedure was chosen, a biopsy and subsequent histological examination could not be performed. In a previous case, similar to this, treated

with the Langenskiöld operation, histological examination showed some evidence of osseo-fibrous tissue in the defect (21). In the present case, the defect was in the lateral periphery of the growth plate. Combined with evidence of continued growth this formed the basis for the decision to insert medial staples. These staples compress the medial physis and thereby reduce the medial growth rate. Then the intact growth plate, surrounding the osseo-fibrous defect, could distend the defect exerting higher force than before, resulting in an increased growth rate. This creates possibilities for regeneration of the defect part of the growth plate. An interesting finding in this case is, that the localization of the condensed area in relation to the tantalum balls in the metaphysis and bony epiphysis in the transverse plane, is the same during the period of observation. On the other hand, the peripheral parts of the growth plate, the metaphysis and the bony epiphysis are growing as normal. This explains, why the condensed area is gradually more centrally situated, and indicates, that the growth in the transversal plane originates mostly from the peripheral parts of the growth plate (15,16,17,22). A similar finding has been demonstrated in an ankle fracture treated with the Langenskiöld operation (21). Most probably this irreversible bony bridge is the final stage with total growth arrest. It is preceded by a reversible process of varying length and with varying end-stage, during which an osseo-fibrous connection in the growth plate is found, resulting in various degrees of growth retardation (9,19,21).

The period of follow-up after the extraction of staples in this case is short. However, the results from the growth analysis and the radiographical appearance of the growth region indicates that, despite the irregularities in the growth plate (corresponding to the area of injury), symmetrical and almost normal growth will probably continue. The growth in the injured region will probably terminate earlier than in the contralateral growth region as has previously been shown to occur in similar cases (20). Furthermore, there might be a loss of correction in this case as the angular deformity was overcorrected before the extraction of the staples, and as the growth potential within the irregularities

could be abnormal. Because of these considerations, this case will be followed clinically and with the RSA until maturity.

In conclusion:

1. The RSA is a sensitive and highly accurate method for analysis of post-traumatic growth pattern in children.
2. The development of the asymmetric growth retardation and the radiographical and clinical growth deformity could be analyzed in detail.
3. Since continued longitudinal growth was registered, the radiographical bony bridge must have corresponded to an osseo-fibrous connection.
4. Insertion of medial staples resulted in increased growth corresponding to the condensed area laterally and in reorganisation of the growth plate. The angular deformity was gradually corrected.
5. Extraction of staples after overcorrection resulted in an almost normal growth rate after a temporary increase medially, probably as a result of elimination of compression forces medially by the staples.
6. Unilateral stapling is an alternative to the Langenskiöld operation for the correction by growth of angular deformities.

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VII

SCINTIMETRIC EVALUATION OF POST-TRAUMATIC AND POST-OPERATIVE
GROWTH DISTURBANCE USING $^{99}\text{Tc}^{\text{m}}$ MDP

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Accepted for publication July 20, 1982.

Bone-seeking agents, especially the $^{99}\text{Tc}^{\text{m}}$ -phosphate complexes, have an established role in the diagnosis of bone diseases. In children, the use of bone-seeking agents has not yet been fully evaluated. However, there is an increasing interest for bone scanning in the diagnosis and follow-up of many disorders.

No reports have been found in the literature of scintimetric analysis of localized growth disorders of the extremities in children. Using ^{85}Sr as tracer, BAUER (1968) demonstrated increased isotope activity at metaphyseal growth zones and related the findings to autoradiography. HARCKE (1978) and MURRAY (1980) discussed the value of skeletal scintigraphy in children with systemic, metabolic, and congenital bone disease. Increased uptake in the growth regions and gradual decrease until maturation was recorded.

GATES & DORE (1975) investigated normal and abnormal suture behaviour by cranial imaging in infants with bone-seeking agents. They found abnormal, non-uniform radionuclide distribution along a prematurely closing suture. When fusion was complete, the nuclide accumulation diminished.

WALTHER et coll. (1980) recommended the use of $^{99}\text{Tc}^{\text{m}}$ MDP imaging in the follow-up of physeal injuries. Diminished activity was found in injured growth regions during treatment in plaster and the non-weight-bearing period.

Normal growth involves in the growth region a considerable incorporation of calcium and phosphate for the mineralization process. It is possible to demonstrate this incorporation quantitatively and qualitatively by bone scanning with calcium, strontium and phosphate. Experimentally, the incorporation is demonstrated with tetracycline labelling (HANSSON 1967).

In dealing with problems of longitudinal growth after injury or following surgery to growth regions, conventional methods for the assessment of information of growth conditions, such as standard radiography and clinical examination are not sufficiently accurate.

The roentgen stereophotogrammetric method (SELVIK 1974) has proven suitable and very accurate for longitudinal growth analysis (ARONSON 1976, BYLANDER et coll. 1981 a and b, KÄRRHOLM et coll. 1982). However, this method is restricted to a few clinical departments. Therefore, a need for alternative non-invasive methods is obvious.

In order to elucidate the value of skeletal scintimetry for the examination of localized growth disturbances following injury or surgery, scintimetry was performed in 8 children provided with markers of 0.5 mm tantalum balls, thus permitting simultaneous roentgen stereophotogrammetric analysis for growth rate determination.

MATERIAL

In 8 children (Tables 1, 2), 32 growth regions were evaluated with $^{99}\text{Tc}^{\text{m}}$ MDP imaging. Of these regions, 25 were provided with markers for the roentgen stereophotogrammetric analysis.

Three growth regions in the proximal tibia and two in the distal femur were stapled according to BLOUNT & CLARKE (1949) 4 to 47 months before the bone scanning. One boy and one girl stapled in the distal femur, were scanned on two occasions, 4 and 14 months apart, respectively.

One growth region in the distal femur was operated upon with physeodesis according to PHEMISTER (1933) 17 months before the bone scanning.

Two growth regions in the distal femur, one in the distal tibia and one in the proximal tibia had sustained physeal injuries resulting in complete growth arrest in one case and in localized growth disturbance in 3 cases. Bone scanning was performed 10 to 32 months after injury.

Table 1

Patients subjected to stapling procedure. The diagnosis, time interval between stapling procedure and scintimetric examination, distribution of chronologic and skeletal age at time of bone scanning and type of surgery. a and b denote first and second scintimetric examination.

Case No.	Sex	Months after surgery	Skeletal age	Chronologic age	Region	Surgery	Type	Diagnosis
1	Boy	14	10 y.	13 y. 6 mo.	Prox.tibia left	Blount stapling	Blount stapling	Congenital fib. aplasia right
2	Boy	16	12 y.	13 y. 2 mo.	Prox.tibia left	Blount stapling	Blount stapling	Congenital hypoplasia right
3	Boy	17	15 y.	15 y. 1 mo.	Prox.tibia right Dist.femur right	Blount stapling Phemister physeodesis	Blount stapling Phemister physeodesis	Traum. growth arrest SH I distal femur left
4 a	Boy	43	12½ y.	13 y.	Dist.femur left	Blount stapling	Blount stapling	Congenital hypoplasia right
4 b		47	13 y.	13 y. 4 mo.				
5 a	Girl	3	12 y.	11 y. 8 mo.	Dist.femur right	Blount stapling	Blount stapling	Hemihypertrophy right
5 b		17	13½ y.	12 y. 11 mo.				

Table 2
Patients subjected to injury. The diagnosis, time interval between injury and scintimetric examination, distribution of chronologic and skeletal age at time of bone scanning and type of injury.

Case No.	Sex	Months after injury	Skeletal age	Chronologic age	Diagnosis	Region of injury
6	Girl	12	8 y.	8 y.	Injury SH type Z (IV)	Distal tibia right
					Injury SH type I	Distal fibula right
7	Boy	10	12 y.	12 y. 4 mo.	Injury SH type IV	Distal femur left lat.
8	Boy	32	13 y	13 y. 8 mo.	Injury SH type I	Proximal tibia left

Chronologic age at the time for scanning was 8 and 13 years, respectively, for the girls and varied between 13 and 15 years for the boys. Skeletal age was assessed according to GREULICH & PYLE (1950) and was 8 and 12 years for the girls and varied between 10 and 15 years for the boys.

METHOD

Scintimetric technique. The patients were given about 200 MBq $^{99}\text{Tc}^{\text{m}}$ labelled methylene-diphosphonate (MDP, Osteolite, New England Nuclear, North Billerica, Mass., USA). In general, static images (0.2 - 0.5 x million counts in 6 min) were obtained 4 to 6 hours after intravenous injection of the agent.

A conventional large field of view (LFOV) scintillation camera with a general purpose parallel hole collimator was used for imaging (LFOV Pho-Gamma, Siemens Gammasonics Inc., Des Plaines, Ill., USA). Conventional scintigrams on polaroid films and transparent film were analyzed.

In addition, count information was stored (matrix 64x64) with a dedicated computer (Gamma 11, Digital Equipment Corp., Maynard, Mass., USA). Counts within regions of interest (ROI) of total or parts of the growth regions were selected and compared in the images. The selections of ROI corresponded to the area of high nuclide activity in the metaphyseal part of the growth plate and adjacent parts of the metaphysis. Background activity was also extracted for soft tissue medially in the thighs and for normal bone in the diaphysis of the femur. At 4 to 6 hours they corresponded only to 2 to 10 and 10 to 15 per cent, respectively, of the activity in the growth region, and no correction for these contributions were made in Tables 3, 4 and 5.

Besides the quantitative information with the computer, image filtering techniques (METZ 1969, GUSTAVSSON & PIZER 1976) were also utilized in an attempt to obtain improved images.

Table 3

Patients subjected to injury or surgery in distal femur. Quantitative analysis of nuclide deposition in growth regions and corresponding levels of longitudinal growth rate in $\mu\text{m}/\text{day}$. Numeric ratios obtained by comparing count rate level of the growth region subjected to injury or surgery, with contralateral intact side using regions of interest selection on images stored and displayed on a dedicated computer system.

Case No.	Distal femur			Scintimetric ratio			Proximal tibia		
	Growth rate		Mean	Med.		Total	Growth rate		mean
	Lat.	Med.		Lat.	Med.		Lat.	Med.	
3 R	0	0	0	0.84*	1.04*	0.99*	0.38**	0.66**	0.53**
L	0	0	0						
7 L	26	39	32	0.81	1.11	0.94	0.78	0.88	0.80
R	-	-	20						
5 a R	5	4	5	0.99	0.85	0.90	1.15	1.15	1.20
L	-	-	37						
5 b R	0	0	0	0.44	0.54	0.48	1.08	0.97	1.03
L	-	-	23						
4 a L	6	13	10	0.51	0.50	0.52	0.81	0.84	0.82
R	-	-	-						
4 b L	8	15	11	0.66	0.75	0.71			
R	-	-	-						

* Comparison between injured right distal femur and contralateral Phemister operated left distal femur.

** Comparison between injured right distal femur and intact right proximal tibia.

Table 4

Patients subjected to injury or surgery in proximal tibia. (For legend see Table 3)

Case No.	Proximal tibia			Scintimetric ratio			Distal femur		
	Growth rate		Mean	Med.	Lat.	Total	Growth rate mean	Scintimetric ratio	
	Med.	Lat.						Med.	Total
1 L	1	1	1	0.54	0.70	0.60	-	0.98	1.17
R	-	-	31				-		
2 L	2	8	5	0.75	0.81	0.78	-	1.04	1.09
R	-	-	28				-		1.02
3 L	0	0	0 ^B	0.53 [*]	0.97 [*]	0.75 [*]	0 ^P	0.46 ^{**}	0.64 ^{**}
R	-	-	8 ⁱ				0 ^F	0.53 ^{**}	0.53 ^{**}
8 L	5	3	4	0.87	0.59	0.70	23	1.31	1.26
R	-	-	13				25		1.42

* Comparison between Phemister (P) operated left distal femur and intact (i) right proximal tibia.

** Comparison between Blount (B) stapled left proximal tibia and intact (i) right proximal tibia.

F Injured right distal femur

Table 5
Patient subjected to injury in distal tibia (For legend see Table 3)

Case No.	Distal tibia			Distal fibula		
	Growth rate	Scintimetric ratio		Growth rate	Scintimetric ratio	
		Med.	Lat.		Med.	Lat.
		Mean	Total	mean	Total	Total
6 R	2	10	6	0.63	0.60	0.61
L	-	-	25	12	-	-
				20		0.51

Roentgen stereophotogrammetry was employed for continuous growth registration (SELVIK, BYLANDER et coll.). Spherical balls of tantalum (diameter 0.5 mm) were used as markers implanted in the metaphysis and bony epiphysis percutaneously or through operative incision in local or general anesthesia. Implantation of markers was performed at the time of stapling or in the 4 cases with physeal injuries 2 (Case 3), 3 (Case 6), 9 (Case 7), and 27 (Case 8) months after injury.

Growth registration was carried out at varying intervals ranging from 1 to 4 months. Growth regions exposed to surgery or injury were provided with 3 or more markers on each side of the growth region and placed medially and laterally in the bone. All patients but one (Case 4) were provided with single tantalum balls on each side of the contralateral growth region as well.

The error of the method has previously been found to be about 30 μm representing about 1 to 2 $\mu\text{m/day}$ at monthly registration intervals (ARONSON).

RESULTS

Of the orthogonal projections, data of the anterior view are analyzed and presented (Tables 3 to 5). The quantitative information about the activity in the growth regions was extracted from computer-stored gamma camera images. The ROI was selected from the total growth regions as well as from the medial and lateral parts. Numeric ratios were obtained by comparing count rate levels of the medial, lateral and total part of the injured or stapled growth region with those of the corresponding intact growth region on the contralateral side (Tables 3 to 5). Intact growth region of the stapled or injured leg was compared with corresponding intact growth region on the other side. The data of the posterior view were found to correspond fairly well with those of the anterior view. The findings from the lateral and medial views were in some instances difficult to correlate with

the other projections but in general a reasonable agreement with findings from the anterior and posterior views was obtained.

The static images of the growth regions had a characteristic appearance. The tracer activity was intense in the metaphyseal part of the area adjacent to the growth plate and gradually diminished in the metaphysis and epiphysis. Occasionally, a small border of slightly increased tracer activity was registered in regions representing the periosteum or on the edge of the bony epiphysis. Where growth disturbance was present, the tracer uptake in the growth region was altered. In cases with growth retardation or growth arrest, the activity was correspondingly reduced or almost absent. Where growth stimulation was present, the activity was increased.

Simultaneous growth rates were derived from the continuous growth pattern analysis using the roentgen stereophotogrammetric technique.

Post-traumatic investigation

Injured distal femur. Two boys (Cases 3, 7) with fractures involving the distal femoral growth plate were examined with scintigraphy 32 and 10 months after injury, respectively.

One of these patients (Case 3) had been struck by a car at the age of 12 years and 5 months (BYLANDER et coll. 1981 b) resulting in a severely displaced distal epiphysis of the right femur. This was classified a type I injury according to SALTER & HARRIS (1963). Tantalum balls were implanted in the distal femur and proximal tibia bilaterally about 2 months after injury. Growth rate analysis showed complete and permanent growth arrest in the injured growth region of right distal femur. The boy was provided with staples according to BLOUNT in the left proximal tibia and operated upon with a PHEMISTER physeodesis in the left distal femur in order to reduce the progressive leg length discrepancy. Scintigraphy was performed 17 months after surgery (32 months after injury). Growth rate analysis at this time revealed no growth in the growth regions subjected to injury and surgery.



Fig. 6. Case 5. A.p. view of left and right knee. Computer presented quantitative images. a) First scintimetric examination. Ratio of distal femur was 0.90. b) Second examination. Ratio was 0.48. Cf. Table 3.

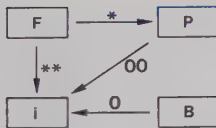


Fig. 1. Case 3. A.p. view of left and right knee. Computer presented quantitative image. White-yellow colours indicate high uptake.

F= Injured right distal femur. i= Intact right proximal tibia. P= Phemister operated left distal femur. B= Stapled left proximal tibia. * Comparison between injured right distal femur and contralateral Phemister operated left distal femur. ** Comparison

between injured right distal femur and intact right proximal tibia.

o Comparison between stapled left proximal tibia and contralateral intact right proximal tibia. oo Comparison between Phemister operated left distal femur and intact right proximal tibia.

Standard radiography showed obliterated growth plates. Growth rate in the remaining intact growth region of the right proximal tibia was decelerating at a rate of 8 $\mu\text{m}/\text{day}$ at the time of scanning.

The qualitative analysis of the gamma camera images showed very low activity in the right injured distal femoral growth region and in the left distal femur which had been operated upon

according to PHEMISTER. Activity in the left stapled proximal tibia especially medially was less than in the intact right proximal tibia where normal activity was found (Fig. 1).

Numeric ratios between the injured right distal femur, and the contralateral growth region, which had been operated upon according to PHEMISTER was 0.99, and showed only slight difference medially or laterally (Table 3). The numeric ratio between the injured right distal femur and the intact right proximal tibia was also assessed and was 0.53.

A boy (Case 7) sustained a hockey injury at the age of 11 years and 6 months laterally in his left distal femur. This was classified according to SALTER & HARRIS as type IV. He developed initially a progressive valgus deformity and was provided with markers 9 months after the injury. Standard radiography at this time revealed a defect laterally in the growth region of the left distal femur (Fig. 2).



Fig. 2. Case 7. Standard film of left injured knee. A.p. view 9 months after injury. Defect in the lateral part of the growth plate in distal femur.

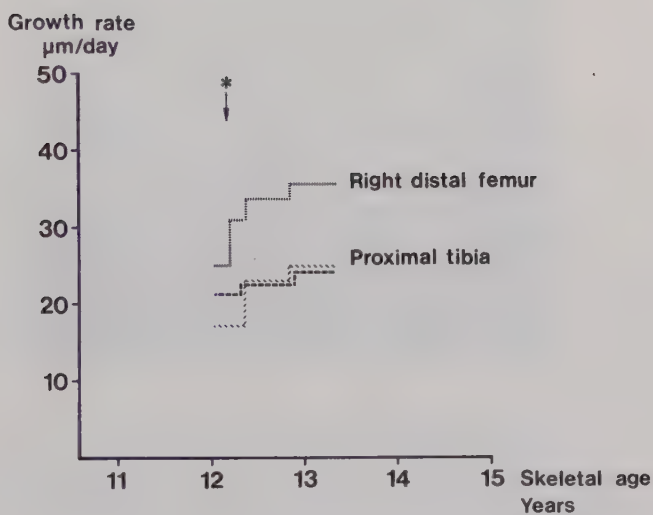
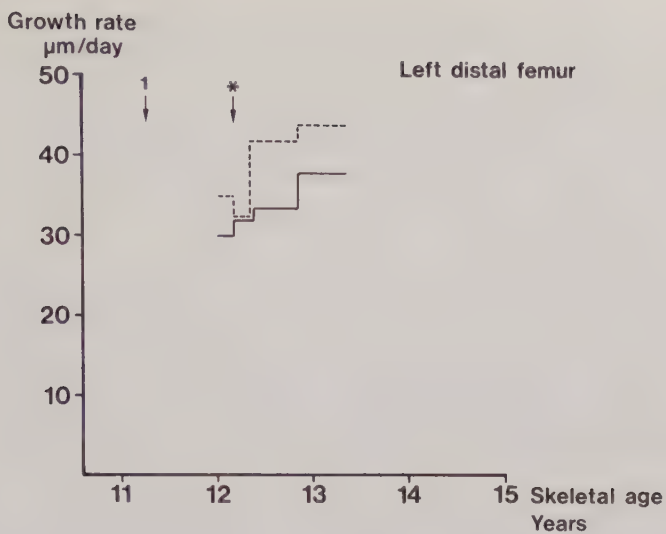


Fig. 3. Case 7. Growth diagrams. a) Left distal femur. Medial aspect (—) and lateral aspect (---). 1= Time of injury. * Time of scintimetric examination. b) Right distal femur (.....) and right proximal tibia (· · · · ·). Left proximal tibia (- · - · -).

Scintigraphy was performed about one month later (10 months after injury). Growth rate analysis (Fig. 3) showed a mean value of 32 $\mu\text{m}/\text{day}$ in the injured growth region, medially 26 $\mu\text{m}/\text{day}$ and laterally 39 $\mu\text{m}/\text{day}$. The intact contralateral side showed growth at 20 $\mu\text{m}/\text{day}$ during the initial period of registration (Table 3).

The gamma camera images showed qualitatively a marked increased activity laterally in the injured distal femoral growth region. This is in correspondence with the numeric ratios of 0.81 medially and 1.11 laterally, between the injured and the contralateral growth regions (Fig. 4).



Fig. 4. Case 7. A.p. view of left and right knee. Computer presented Metz filtered analogue image. An area of distinctly increased activity (white arrow) in the injured part of left distal femoral growth region.

Injured distal tibia and fibula. A girl (Case 6) sustained a supination-adduction stage II injury to her right ankle when she fell from a swing at the age of 7 years and 10 months (KÄRRHOLM et coll.). Closed reduction and percutaneous fixation with Steinmann pins was performed and she was provided with markers in distal tibia and fibula bilaterally about 2 months after injury at pin extraction. Growth rate analysis showed, at scintigraphy 10 months later (12 months post-traumatically), growth retardation, 6 $\mu\text{m}/\text{day}$ and 12 $\mu\text{m}/\text{day}$, in the injured distal tibia and fibula, respectively. Medially and laterally the growth retardation in the injured distal tibia was 2 and 10 $\mu\text{m}/\text{day}$, respectively. The patient developed a progressive varus deformity.

The analysis of the gamma camera images revealed reduced activity in the injured growth regions. The quantitative analysis between the injured and the contralateral intact growth regions showed correspondingly low numeric ratios, 0.61 and 0.51, at the distal tibia and fibula, respectively. The asymmetric growth, as found by the roentgen stereophotogrammetric analysis, was not possible to demonstrate in the scintimetric analysis.

Injured proximal tibia. A boy (Case 8) was brought to the local hospital after an accident on a motor-bike when 11 years old with a diaphyseal fracture in the left femur, an undisplaced fracture through the left patella, and soft tissue injury around the left knee. He was initially treated with left proximal tibial pin traction and later on with intra-medullary nailing of the left femur. A Slocum procedure was performed 12 months later because of a dislocated patella in the left knee. The boy developed a progressive valgus deformity in his left knee and reexamination of the films from the time of injury revealed a physeal injury almost undisplaced in the left proximal tibia, which was classified according to SALTER & HARRIS as type I injury. New standard radiography (26 months after trauma) showed a defect in the lateral part of the left proximal growth region of the tibia. The boy was provided with markers of tantalum balls in the proximal tibia and distal femur bilaterally 27 months after injury.

Growth rate analysis showed reduced and asymmetric growth in the injured left proximal tibia, laterally 3 $\mu\text{m}/\text{day}$ and medially 5 $\mu\text{m}/\text{day}$. Growth rate in the right intact proximal tibia was 13 $\mu\text{m}/\text{day}$ and in the right and left distal femur 25 $\mu\text{m}/\text{day}$ (Table 4).

Because of the progressive angular deformity, the patient was stapled medially in the left distal femur and the left proximal tibia in order to correct the deformity.

Scintigraphy was performed at the time of stapling, 32 months after injury.

The qualitative analysis of the gamma camera images showed reduced uptake laterally in the left proximal tibia. Numeric ratios were correspondingly low, 0.87 and 0.59 medially and laterally in the proximal tibia, indicating general growth disturbance which was especially marked in the left lateral proximal tibia (Table 4).

Intact growth regions. All contralateral growth regions of the 4 children with physeal injuries were provided with markers thus permitting roentgen stereophotogrammetric analysis of the longitudinal growth rates. However, it was only possible to compare the contralateral intact growth regions in 2 children (Cases 7, 8). In the remaining 2 children, the contralateral side was either operated upon with a PHEMISTER physeodesis (Case 3) or both the distal tibia and the distal fibula were injured (Case 6).

Intact left and right proximal tibia (Case 7) showed growth rates of 18 and 19 $\mu\text{m}/\text{day}$. The qualitative analysis of gamma camera images revealed normal similar activity in the growth regions. However, in the qualitative analysis, the numeric ratios between the intact left proximal tibia of the injured knee and the contralateral side were low, 0.80, and differed medially and laterally, 0.78 and 0.88, respectively. The intact left and right distal femurs (Case 8) showed growth rates of 23 and 25 $\mu\text{m}/\text{day}$. The qualitative analysis showed bilaterally increased activity

laterally, slightly more marked in left distal femur. The quantitative analysis revealed no significant differences; the numeric ratios were 1.31 and 1.26 medially and laterally. A numeric ratio of 1.42 between total growth regions indicated increased activity in the left distal femur contradicting the growth rate analysis which showed a slightly increased growth rate in the right distal femur.

Postoperative investigation

Stapling of distal femur. Two patients (Cases 4, 5) stapled in the distal femur were examined with scintigraphy 43 and 47 and 3 and 17 months after surgery, respectively.

Growth rate analysis in Case 4, provided with markers exclusively in the stapled distal femur, showed a growth rate of about 10 $\mu\text{m}/\text{day}$ (4 a), when the first scintimetric investigation was performed (43 months post-operatively). The roentgen stereophotogrammetric investigation revealed asymmetric growth, medially 6 and laterally 13 $\mu\text{m}/\text{day}$ (Table 3).

The gamma camera images showed reduced activity, but with no marked difference, medially and laterally in the stapled growth region. The quantitative analysis between total stapled and intact contralateral growth region revealed a numeric ratio of 0.52. Equal ratios were 0.51 and 0.50, medially and laterally, despite the asymmetric growth found by the roentgen stereophotogrammetric analysis (Table 3).

At the second bone scanning procedure (47 months post-operatively), growth rates had increased to 11 $\mu\text{m}/\text{day}$ in the stapled region (4 b), and asymmetric growth had increased medially to 8 $\mu\text{m}/\text{day}$ and laterally to 15 $\mu\text{m}/\text{day}$ (Table 3). The qualitative analysis showed a slightly increasing, but still reduced activity at the stapled growth region compared with the contralateral intact side, with a slight difference medially and laterally. The quantitative analysis showed accordingly an increased numeric ratio of 0.71, medially 0.66 and laterally 0.75 (Table 3).

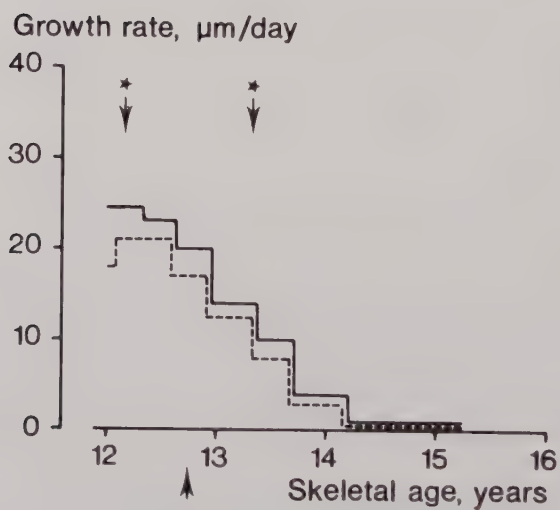
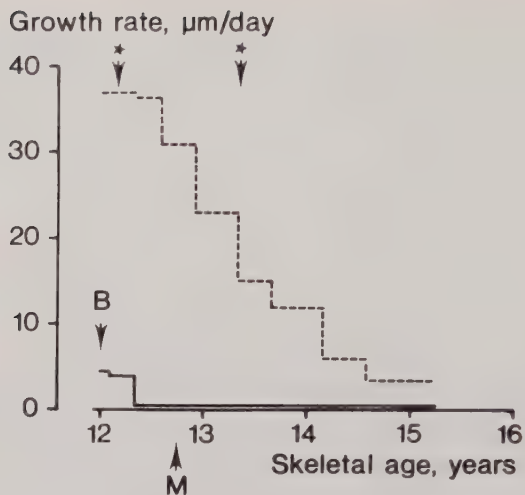


Fig. 5. Case 5. Growth diagrams. a) Distal femur. b) Proximal tibia. Intact left side (---) and stapled right side (—). * First and second scintimetric examination. B= Blount stapling of right distal femur. M= First menstruation.

The stapled growth region in Case 5 showed markedly reduced growth rates (Fig. 5 a), 4 $\mu\text{m}/\text{day}$ at first scanning (5 a) and below 1 $\mu\text{m}/\text{day}$ on the second (5 b) and 37 $\mu\text{m}/\text{day}$ in the intact contralateral growth regions, respectively (Fig. 5 b).

The qualitative analysis of the gamma camera images revealed reduced activity in the stapled distal femoral growth region (Fig. 6 a) and this was further reduced at the second examination (Fig. 6 b). Quantitatively, the numeric ratio between the stapled and the contralateral intact growth regions, was correspondingly low at the first scanning procedure (3 months post-operatively), 0.90 (Table 3). On the second occasion (17 months post-operatively) the numeric ratio had decreased to 0.48 (Table 3). The difference between the medial and lateral aspects was found to be in accordance with the growth rate analysis, on the first occasion but reversed at the second scanning procedure when no growth could be registered with the roentgen stereophotogrammetric method.

Stapling of proximal tibia. Three patients (Cases 1, 2, 3) stapled according to BLOUNT were examined with scintigraphy 14, 16, and 17 months after surgery. Growth rates of stapled growth regions were in all 3 cases markedly lower than in the contralateral intact growth region. At the time of scintigraphy (14 months post-operatively) the growth rate for Case 1 in the stapled proximal tibia was approximately 1 $\mu\text{m}/\text{day}$. The corresponding growth rate of the contralateral intact growth region was 31 $\mu\text{m}/\text{day}$. Analysis of the gamma camera images showed reduced activity in the stapled growth region and demonstrated a less defined congruity between the medial and lateral parts than in the contralateral intact growth region of the proximal tibia. Corresponding numeric ratios, medially 0.54 and laterally 0.70, showed an asymmetry that could neither be demonstrated visually at the qualitative analysis of the images nor in the growth rate analysis. However, the numeric ratio between the total stapled and the contralateral growth regions was 0.60, which is in good correspondence with the qualitative and roentgen stereophotogrammetric analyses (Table 4).

Asymmetric growth was present in one patient (Case 2). This patient developed a progressive varus deformity. At the time of bone scanning (16 months post-operatively) the growth rates medially and laterally were 2 and 8 $\mu\text{m}/\text{day}$, respectively.

The analysis of the gamma camera images revealed reduced activity in the stapled growth region but no significant difference medially or laterally. The numeric ratio between the stapled and contralateral intact growth region in proximal tibia was 0.78, medially 0.75 and laterally 0.81 (Table 4).

Differences in the numeric ratios, medially 0.53 and laterally 0.97, could be demonstrated in Case 3. As in Case 1, the qualitative analysis revealed a slight incongruity medially and laterally (Fig. 1). Growth rate analysis at the time of scanning showed no growth in the stapled proximal tibia, and 8 $\mu\text{m}/\text{day}$ in the contralateral intact side. This is in correspondence with the total numeric ratio of 0.75 between the stapled and the intact growth regions (Table 4).

Intact growth regions. The activity between the intact growth regions was recorded in Cases 1, 2, 4, and 5. Comparison with simultaneous growth rate analysis was only possible in Case 5 since no markers were implanted in the intact growth regions in Cases 1, 2, and 4.

Numeric ratios (Table 3, 4) between all intact growth regions of the stapled and the contralateral sides were obtained and a qualitative analysis performed.

The qualitative analysis between the intact growth regions showed no significant differences in activity. Quantitatively the numeric ratios were approximately 1.0 in all cases except Case 4 where the numeric ratios were on the first and second examinations, 0.82 and 0.89, respectively (Table 3).

Analysis of the gamma camera images in Case 5 (Fig. 6) showed no significant differences medially or laterally in the proximal tibia at the first and second scanning procedures (5 a and b) and corresponding numeric ratios were found. These findings correlated well with the growth rate analysis (Fig. 5) in the right and left proximal tibias, 23 and 21 $\mu\text{m}/\text{day}$, respectively, at the first scanning procedure (3 months post-operatively), and 13 and 8 $\mu\text{m}/\text{day}$, respectively, at the second scanning procedure (17 months post-operatively).

DISCUSSION

Methodology. Absence of precise information on longitudinal growth conditions in separate growth regions in children with localized disturbance has previously made scintigraphic bone imaging of these regions difficult to evaluate. With the introduction of the roentgen stereophotogrammetric method (SELVIK) a suitable method for highly accurate longitudinal growth analysis presented a mean for comparison. Thus, it was possible to analyze the activity in 32 growth regions and to correlate obtained data to longitudinal growth rates simultaneously derived from growth rate analysis.

The roentgen stereophotogrammetric technique provides data about translations and rotations about the 3 main axes (SELVIK). In this type of growth investigations the translation along the longitudinal axis is of prime interest for analysis of the longitudinal growth rate from the physal regions of the long bones (ARONSON, BYLANDER et coll. 1981 b, KÄRRHOLM et coll.). Contrary to this, the information from scintimetric investigations in growing individuals using $^{99}\text{Tc}^{\text{m}}$ MDP is very complex in origin. $^{99}\text{Tc}^{\text{m}}$ MDP is incorporated during growth and remodelling of bones. Thus, the localization of the nuclide occurs in the resorption cavities of calcified cartilage and mineralized bone temporarily and in the mineralization process of cartilage and bone more or

less definitely (CHRISTENSEN & KROGSGAARD 1981). A corresponding localization of the mineralization process has previously been demonstrated for tetracycline (HANSSON 1964, 1967).

However, the radiation dose is low with the $^{99}\text{Tc}^{\text{m}}$ MDP in recommended doses for children (SAENGER & KEREIAKES 1975). Quantitative and qualitative analyses of the orthogonal anterior view were performed. Valuable information was obtained in static images, using a parallel hole collimator, 4 to 6 hours after intravenous injection of the agent. The initial vascular phase was in some early cases recorded but did not add further information. The orthogonal projections of posterior, lateral and medial view were found to satisfactorily correlate with the anterior images. However, some irregularities were revealed, especially in images of lateral and medial projections. The converging pinhole collimator was utilized on some occasions but significantly improved images were not obtained.

Growth analysis. In 8 children with various types of localized growth disturbances, the uptake in the growth regions at the knee or ankle was correlated with longitudinal growth rates at the same time derived from growth rate analysis with the roentgen stereophotogrammetric method. This method has been found suitable for a highly accurate longitudinal growth rate analysis (SELVIK, ARONSON, BYLANDER et coll., KÄRRHOLM et coll.).

Diminished growth capacity in the growth region can be demonstrated by standard radiographic technique. The narrowing, fusion, or localized defect in the growth plate may indicate growth disturbance. However, the standard radiography and tomography have proven insensitive and reveal late the alterations of growth. The present results show that the bone-imaging procedure is a sensitive alternative technique for the demonstration of localized growth disturbance. The isotope activity in growth regions represents the metabolic rate of calcification whereas the roentgen stereophotogrammetric method provides longitudinal growth rate information with high accuracy.

This difference was demonstrated in the following case. A boy (case 3), with an injury of the right distal femur resulting in total growth arrest, was operated upon with Plemister physeodesis in the left distal femur and Blount stapling in the left proximal tibia. The activity in the distal femur bilaterally indicated remaining metabolic activity although no growth was registered by the roentgen stereophotogrammetric analysis.

An interesting case is the boy (Case 7) who sustained an injury to his left lateral distal femur. A progressive valgus deformity developed and standard radiography showed a osseo-fibrous defect laterally in the left distal femoral growth region. However, increased activity was seen laterally (10 months after the injury) and the growth rate analysis confirmed the finding. Growth stimulation persisted laterally later on during the observation and the valgus deformity slowly diminished.

The distal tibial and fibular growth regions were examined in one girl (Case 6). The distal fibular growth region was well separated from the distal tibial growth region in the bone-image. The reduced activity of injured right distal tibia and fibula correlated well with the growth analysis. However, no differences medially or laterally of the tibia could be demonstrated indicating the difficulty to reveal asymmetric growth in this region.

A boy (Case 8) represents growth disturbance following injury in the proximal tibia. Reduced activity was found, and was especially marked laterally. The increased uptake in the distal femur laterally corresponded well to the growth analysis, which revealed slightly asymmetric growth. This is probably an expression of spontaneous correction.

Qualitative and quantitative analyses of the gamma images in 2 cases (Cases 4, 5) stapled in the distal femur and examined with bone imaging on 2 occasions correlated well with and were in good agreement with the growth rate analysis. The second examination (Case 4 b) showed increasing numeric ratios, especially

laterally, illustrating insufficient growth retardation due to loosening and extrusion of staples (BYLANDER et coll. 1981 a).

Corresponding diminished uptake was recorded at the second examination (17 months post-operatively) in Case 5 b. Thus, longitudinal growth rate analysis showed decreasing growth rates medially and laterally. No growth was recorded at the time of second bone imaging procedure.

Numeric ratios between the stapled and contralateral intact regions in the proximal tibia were, in general, low. The qualitative analysis of the stapled growth regions showed a correspondingly diminished uptake. Thus, the qualitative and quantitative nuclide examinations showed good agreement and are of value when analyzing children with localized growth disturbance.

Concerning the medial and lateral aspects of the stapled growth regions in the proximal tibia, the increased numeric ratios found laterally could be explained by difficulties in identifying the growth region due to interference and overlapping of the proximal fibular growth region. However, corresponding differences were not found between the intact growth regions in the proximal tibia. It is well recognized that the insertion of staples laterally in the proximal tibia is occasionally difficult (GREEN & ANDERSON 1957, BLOUNT 1971). This is probably the most feasible explanation for the fact that asymmetric growth more commonly occurs in this region following stapling. However, the roentgen stereophotogrammetric analysis revealed pronounced asymmetric growth in only one of the 3 cases stapled in the proximal tibia.

SUMMARY

Scintimetry with $^{99}\text{Tc}^{\text{m}}$ MDP was performed in 32 growth regions in 8 children with localized growth disturbances after surgery or injury. The results were compared with the simultaneously performed growth rate analysis using roentgen stereophotogrammetry. A quantitative and qualitative analysis of the nuclide bone images of the anterior view was performed. Numeric ratios, obtained by comparing count rate levels of injured or operated growth region with the corresponding contralateral region, are presented and a satisfactory correlation with the roentgen stereophotogrammetric growth rate analysis was found. Nuclide bone imaging of growth regions at the knee and ankle provides valuable and significant information about growth and was found to be a clinically useful method when combined with standard radiographic techniques to evaluate growth conditions.

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